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AN OVERVIEW OF THE SOVIET EFFORT IN UNDERGROUND GASIFICATION OF COAL

D. W. Gregg
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January 29, 1976

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Abstract

We review underground coal gasification as developed in the USSR since 1928. We present most of the data as illustrations, reviewing the Soviet coal gasification power stations, the problems encountered in specific types of coal areas, and the methods used to surmount these problems.

Introduction

This paper contains the figures and associated comments from a talk on the Soviet effort in underground coal gasification presented at the 1975 Gordon Research Conference on Fluids in Permeable Media, August 11-15, 1975.[1] The material covers the location of the gasification stations, the geological nature of the coal, the underground design of the gasification systems, performance data, and an attempt to explain why particular design choices were made.

Upon embarking on this review of the Soviet work in underground gasification of coal it very quickly became clear to us that the amount of effort expended by the Soviets far exceeds the summation of efforts by other nations. The Soviet decision to pursue underground gasification of coal was made in 1928, and the first field experiments were performed in 1933.[2,3] Their work has continued up to the present, with varying levels of effort that appeared to peak in the late 1960's. The information in Ref. 4 indicates that there were as many as 3000 people working in the effort in 1963. It appears that the effort might have more than doubled by the late 1960's, and then fallen off dramatically by the early 1970's.

The reduction in effort was probably due to their discovery of large resources of natural gas, and the construction of the necessary pipelines for its distribution. A crude economic estimate, taking into consideration the numerous commercial plants they constructed and operated as well as the number of people involved over the past 47 years, indicates that it might take as much as 10 billion 1976 dollars to reproduce their work.

Because only the Soviets have operated numerous commercial coal gasification power plants over long periods of time, it is important to understand not only what their final process designs looked like, but also why they settled on such designs. It is easy to conceive of numerous designs for the underground gasification of coal that address one particular problem or another, but in the operation of a successful commercial process it is obvious that all the problems that nature is going to generate have to be dealt with simultaneously in a satisfactory and harmonious manner. Only the Soviets have demonstrated that they have a system design that can be operated repeatedly in a predictable manner and can be transferred from one area to another where there are large differences in the geological nature of the coal seams.

The purpose of underground gasification of coal is to convert coal into a combustible gas by carrying out the appropriate chemical process underground. The Soviets saw this as a possible means of recovering the heating value of the coal without having to employ men in the dangerous and unhealthy job of underground mining. Air, and sometimes oxygen-enriched air, is used to partially combust the coal to produce a combustible gas. The essential equations describing the process are as follows:

$$\text{Coal} + \text{heat} \rightarrow \text{char (carbon)} + CH_4 + H_2 + \text{tars} + CO_2 + CO + \text{etc.} \quad \text{(pyrolysis)}, \qquad (1)$$

$$\text{Char} + O_2 \rightarrow CO + CO_2 + \text{energy}, \qquad (2)$$

$$\text{Char} + H_2O \rightarrow CO + H_2 - \text{energy}. \qquad (3)$$

It is important to add water to use the excess energy released via Eq. (2) to produce a combustible product via Eq. (3). In practice, the Soviets found that generally the amount of water intruding into the gasification zone naturally was more than sufficient for air gasification; therefore no attempt was made to add water to the injected gas.

In this paper we discuss the location of the Soviet gasification stations, the geological conditions at the sites, the basic process designs and their operating parameters, and the reasons why certain critical choices were made. The bulk of the discussion is in the form of illustrations (Figs. 1-42) and their captions in the section *Soviet Methods of Underground Coal Gasification*. In the section *Conclusions* we briefly discuss the state-of-the-art in coal gasification as reached in the Soviet effort.

Conclusions

The Soviet underground coal gasification systems for horizontal and steeply dipping beds, which are essentially the same basic design at different angles to the surface, are deceptively simple. However, it has been demonstrated repeatedly that they can be made to operate successfully in an extremely complex environment, a burning coal seam with a subsiding roof. The basic system design can also be transferred from one coal seam to another with reasonably predictable results, in spite of the wide variations in the geological conditions that exist between coal seams. It is therefore useful to understand the design in terms of how it handles a number of easily recognized physical phenomena that must be dealt with in any design for the underground gasification of coal.

Gas Leakage — One design requirement of an underground coal gasification process is the ability to minimize the loss of both the injected blast and the product gas, which can leak through cracks to the surface or other surrounding formations. This can be a strong effect since gas losses increase with the square of the pressure. It is clear that maintaining a gas-tight zone is a formidable task since as coal is removed, the roof must eventually subside, especially for the case where a high fraction of the coal is recovered over a large area. Such subsidence forms very permeable cracks to higher formations — sometimes all the way to the surface, which allows gas to leak away from the process zone.

Since the extent of these leakage cracks is unpredictable as the combustion zone moves across a coal seam, it is important to design the system so that it has minimum sensitivity to such leaks. The only way this can be done is to operate the system at the lowest possible pressure and make certain that the permeability in the coal between the injection and exhaust holes is always much higher than the permeability through subsidence in the area between the reaction zone and the surface. The Soviets accomplished this by establishing highly permeable paths in the coal (linking) between the injection and exhaust holes before gasification and then operating at the lowest pressure consistent with production requirements. They also helped seal the cracks at the surface by bulldozing them full of mud.

High Gas Flow Rate at Low Pressure — A high gas flow rate is necessary to compensate for the water intrusion rate as well as to maximize the channel width and thus resource recovery for a line of drilled holes. It is also important to achieving an economically high production rate. This requirement is tightly coupled to the gas leakage problem discussed above. (Increased flow rates require increased pressure drops.) The high gas flow rates can be maintained with minimum leakage only if the permeability between the injection and production holes exceeds some minimum value. The Soviets generally used gas flow rates of 3,000 to 10,000 m^3/hr with driving pressures that did not exceed approximately 2.5 atm.

An advantage of these low operating pressures was the possibility of using high-capacity, relatively inexpensive blowers to supply the air. However, this advantage is not important when using oxygen/steam for the gasification.

Directional Control of Gas Flow — Directional control of gas flow is essential for a reproducible system. It is only by establishing flow control, and the consequent reproducibility, that we can begin to engineer a system which maximizes resource recovery or optimizes the economics. (These criteria may not lead to the same system.) This requires a means of establishing control which is insensitive to variations in geology or coal type.

The Soviets achieved directional control using highly permeable linkage paths (with predetermined spacing) at the bottom of the coal seams. These paths make the process insensitive to variations in the natural coal permeability and thus enable us to design a predictable system, after obtaining initial scaling data. The directional control of the gas flow also insures that the gas will flow to the exhaust pipe instead of spreading uncontrollably throughout the formation.

High Surface Area Reactor with High Permeability — High permeability is needed for the reasons stated above. The high surface area, which infers a zone of rubble without bypass channels, is almost always needed for any efficient gas-solid reaction. In such reactions, the reaction rate is limited by the surface area of the solid, since this is where the initial reactions must take place. In the Soviet system for horizontal coal seams the flame front undercuts the coal, which then falls into the void to form rubble. The system for steeply dipping beds forms rubble by causing coal to fall into the void created at the bottom, where combustion is initiated. It is also expected that the reaction rate is enhanced at the coal surfaces in the upstream region of the channel, where the channel width is many times the thickness of the coal seam, by thermal spalling of the coal face.

Liquid Control — One of the primary effects that liquids (water and pyrolysis tars) can have on the propagation of the flame front in a horizontal seam is to cause the flame front to move preferentially along the top of the coal seam. This occurs because liquids, being much more dense than the gases, migrate to the bottom of the seam. The gas flow, and thus the flame front, will then traverse the top of the seam.

A difficulty thus arises. Once a channel is formed across the top of the seam, the coal ash tends to seal the bottom of the channel preventing further combustion of coal and resulting in very poor resource use. The Soviet process minimizes this effect by initially forming the channel at the bottom of the seam in the preparatory linking step. The channels are kept quite hot all during the process so that any liquids that intrude into the region, as well as liquids formed by pyrolysis, are carried out as vapors. This keeps the channels clear to gas flow. Bringing all the liquids off as vapors also allows us to recover the coal tars, which have economic value as liquids.

Minimized Contamination of the Aquifer with Phenols — The mechanism for total liquid removal described above also insures the removal of phenols formed in the pyrolysis of the coal. They are removed efficiently as vapors, never being allowed to condense, with the efficiency of the removal being enhanced by a "steam flush" created by intruding water intersecting the hot channel. They are thus not left behind to contaminate the underground water supply.

Maximized Survival and Spacing of Access Pipes — A principal portion of the cost of carrying out underground coal gasification is associated with the access pipes. It is thus important to maximize the probability of the survival of the piping and the removal for reuse of the casing during the process. It is also important to maximize the coal removed per hole, which dictates the tradeoff between fractional resource recovery and hole spacing.

The Soviet designs place the access holes so that they are removed from the subsiding zone until they are no longer needed. This both maximizes the probability of their survival and also makes it possible to pull the casing and reuse it. It also eliminates the need to design heavy access pipes that will survive the earth motion associated with subsidence. The Soviets also improve the survival of the casing in the exhaust holes by cooling the exhaust gases with a water spray, taking care not to cool it so low that liquids condense. This reduces pipe corrosion and thus extends pipe life.

It is hard to prove that the pipe spacing was maximized in terms of any other possible system. However, there were certain features incorporated that are essential for a large pipe spacing:

- The highly permeable channel between the injection and exhaust holes is essential if one is to have a large pipe spacing while retaining high gas flow rates at low pressure drops.
- The reproducibility of the system allows us to optimize the pipe spacing.

<u>A System that is Adaptable to Thick or Thin Seams</u> — The Soviets have found no maximum limit in thickness of coal seams for their processes. They have operated in seams up to 65 ft thick with no indication that they are approaching a limit. (There are very few coal seams in this country over 100 ft thick.)

However, the Soviets did find that there was a limit on how thin a seam could be. If the seam thickness fell below 3 to 4 ft, the heating value of the gas became unusably low. As the coal seam gets very thin, the fraction of the heating value of the coal that goes into heating the surrounding rock increases to a prohibitive level.

<u>No Men Underground</u> -- The Soviet design requires no men underground, which is not true of the British design or of earlier Soviet designs. It is an extremely important feature since once gasification is initiated, it is almost impossible to guarantee that the toxic product gases would not leak into nearby mine workings.

<u>A System that Can Be Applied to Multiple Layered Coal Seams</u> — The Soviets have been able to sequentially gasify multiple layers of coal starting with the top seam and working down.

<u>A Continuous System as well as an Intermediate Load System</u> — The Soviet system sweeps continuously across a coal seam, and therefore has a predictable electricity base load. There is also a need for electricity on an intermittent basis to supply peak loads. The Soviet system has shown, under some circumstances, the capability of being turned on and off in time periods of a few hours, which might make it useful for supplying intermittent loads.

Constant Gas Composition vs Time — The design of the Soviet system makes it possible to maintain a product gas composition that is quite constant in its heating value. This requires one additional control: the flow rate is varied to "fine tune" the heating value.

Reproducibility, Predictability, and Control — The performance of the process design is reproducible and predictable within reasonable limits from one generator to another, within the same coal seam as well as when transferred from one coal-bearing area to another. It has been possible to make it operate in widely varying coal types: lignite, subbituminous, and bituminous. It has also been demonstrated to have adequate controls to achieve a constant gas quality and a high resource recovery; 75% or more of the coal is consumed with recovery of between 50 and 70% of the heating value of the consumed coal.

Minimum Sensitivity to Coal Swelling -- The large-dimension channels formed in the linking phase are not likely to be plugged by moderately swelling coals.

Minimum Sensitivity to Flame Front Channeling — The Soviet system makes no attempt to avoid the natural tendency of flame front channeling; in fact, it encourages it. However, the gas quality is insensitive to such channeling because the channels through the coal seam are made very long.[5]

Simplicity of System Design and Operation — The Soviet design is exceptionally simple (deceptively so), as is its operation. It involves only the technology of drilling a simple pattern of holes (although slant drilling is not always easy) and handling compressed air. The end result is that it is insensitive to the many uncontrollable physical phenomena that operate in the process. Such simplicity and insensitivity make the process technically possible.

Soviet Methods of Underground Coal Gasification

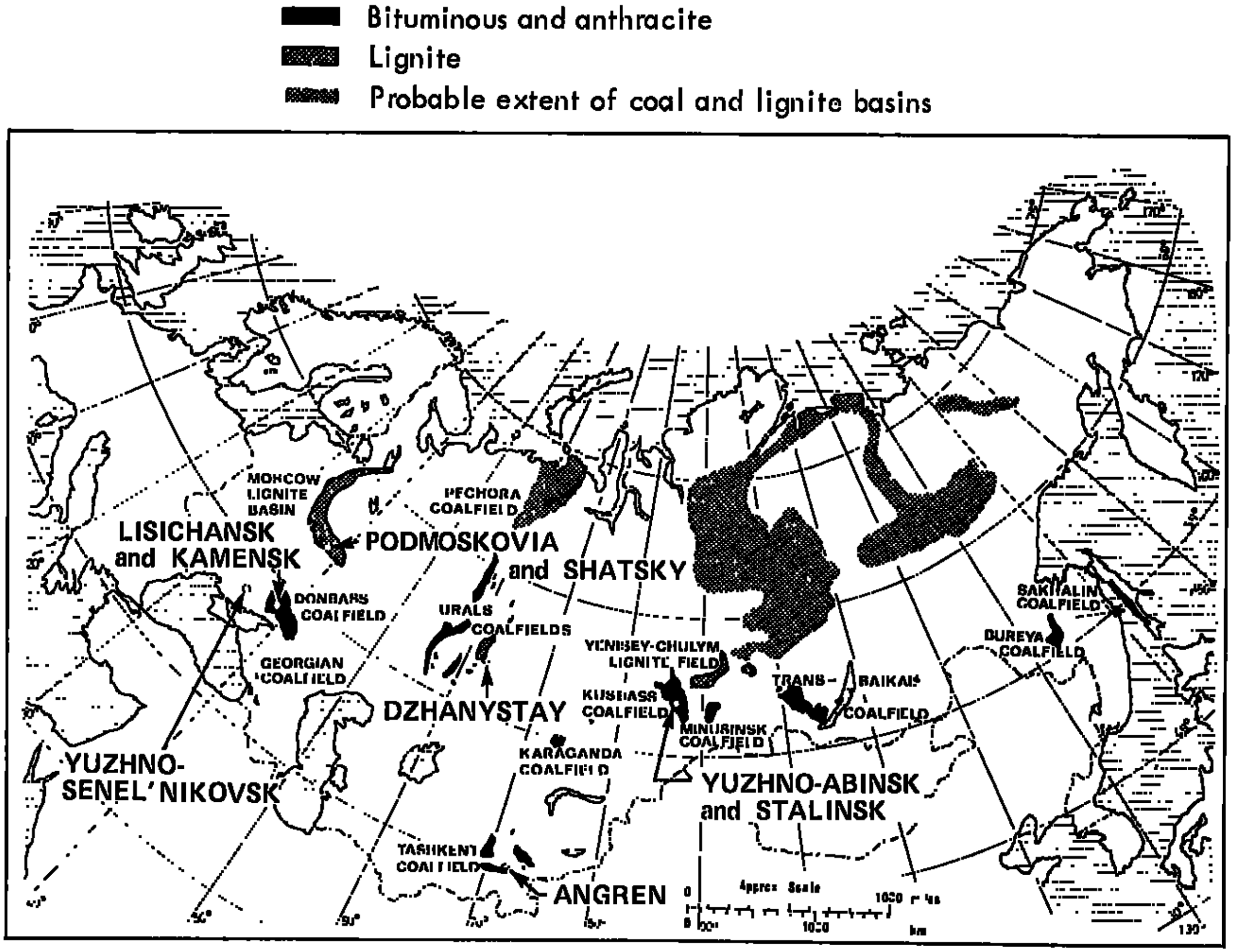


Fig. 1. Map of USSR showing underground coal gasification sites. This map, taken from Ref. 6, shows the Tashkent coalfield as bituminous; it is our belief, however, that the Angrenskaya underground gasification station associated with the field uses brown coal.[5,7-9] It is our understanding that three gasification stations, Podmoskovia (at Lula), Yuzhno-Abinsk, and Angren, are still operational, but not necessarily on a continuous basis.

Donbass (Donets Basin)

Shakhta	(Anthracite 1933)
Lisichansk	(Oldest pit 1933)
Gorlovka	(Experimental 1935)
Kamensk	(Under construction 1960)

Lisichansk

Coal characteristics

1. Bituminous (6-16% ash, 25-35% volatiles, ~15% H_2O, 1-5% sulfur)[10].
2. Steeply dipping (20-60°)[10].
3. Thin seams[10] (0.4-1.5 m) as deep as 400 m.
4. 4500-5000 kcal/kg (8000-9000 Btu/lb) coal in the seam[10].

Gasification characteristics

1. 800-1000 kcal/m^3 (90-112 Btu/scf)[10].
2. 1.5×10^8 m^3/yr (1.5×10^9 Btu/day) in 1959[10].

Economics

1. 55 rpls/1000 m^3 (1.56 rpls/1000 scf) in 1959[10].

Kuzbass (Kuznets Basin)

Lenin pit	(1933)
Yuzhno-Abinsk	(Podzemgaz station 1955)
Stalinsk	(Under construction 1960)

Yuzhno-Abinsk

Coal characteristics

1. Bituminous (4-10% ash, 20-30% volatiles, 5-8% H_2O[10].
2. Steeply dipping (55-70°)[11].
3. 23 seams 2-9 m thick[11].
4. 5000-6000 kcal/kg (9,000-10,800 Btu/lb) coal in the seam[10].

Gasification characteristics

1. 1000 kcal/m^3 (112 Btu/scf)[10].
2. 3.9×10^8 m^3/yr (4.1×10^9 Btu/day) in 1965[11].

Economics

1. 29.5 rpls/ 1000 m^3 (0.8 rpls/1000 scf) in first quarter of 1959[10].

Fig. 2. Data on Lisichansk and Yuzhno-Abinsk. The important points here are that both areas have steeply dipping beds and bituminous coal, but Lisichansk has much thinner seams than Yuzhno-Abinsk.[10,11]

Podmoskovnyi (Moscow Basin)

Krutova mine	(First primitive trials 1932)
Podmoskovia station	(At Tula, experimental 1940)
Shatskaya	(1960)

Tula

Coal characteristics

1. Lignite (Hard brown coal, 27-60% ash, 17-27% volatile, 20-30% H_2O)[10].
2. Horizontal.
3. Roof is loam-sand-loam (plastic), descends uniformly and compacts bed[12].
4. 2-4 m thick, 40-60 m deep[12].
5. 2000-5000 kcal/kg (3600-9000 Btu/lb) for dry coal[10].

Gasification

1. 700-900 kcal/m^3 (79-101 Btu/scf)[10].
2. 4.6×10^8 m^3/yr.

Economics

1. 36.3 rpls/1000 m^3 (1 rpl/1000 scf) in 1959[10].

Angren (Near Tashkent,, 1962)

Angren

Coal characteristics

1. Lignite (hard brown coal, 11% ash, 25-30% volatile, 30% H_2O, 1% sulfur)[10].
2. Horizontal (5-15° dip)[10].
3. Roof is heavy, gas-impermeable layer of kaolin[4].
4. 4-24 m thick, 110-250 m deep[5].
5. 3650 kcal/kg (6600 Btu/lb)[10].

Gasification

1. 800-850 kcal/m^3 (90-96 Btu/scf)[13].
2. 1.4×10^9 m^3/yr (12.6×10^9 Btu/day) in 1965[13].

Economics

1. 16 rpls/1000 m^3 (0.5 rpls/1000 scf) in 1965[13].

Fig. 3. Data on Podmoskovia and Angren. The important points here are that both areas have horizontal beds and lignite coal (brown coal), but Podmoskovia has much thinner coal seams than Angren.[4,5,7,10,12,13]

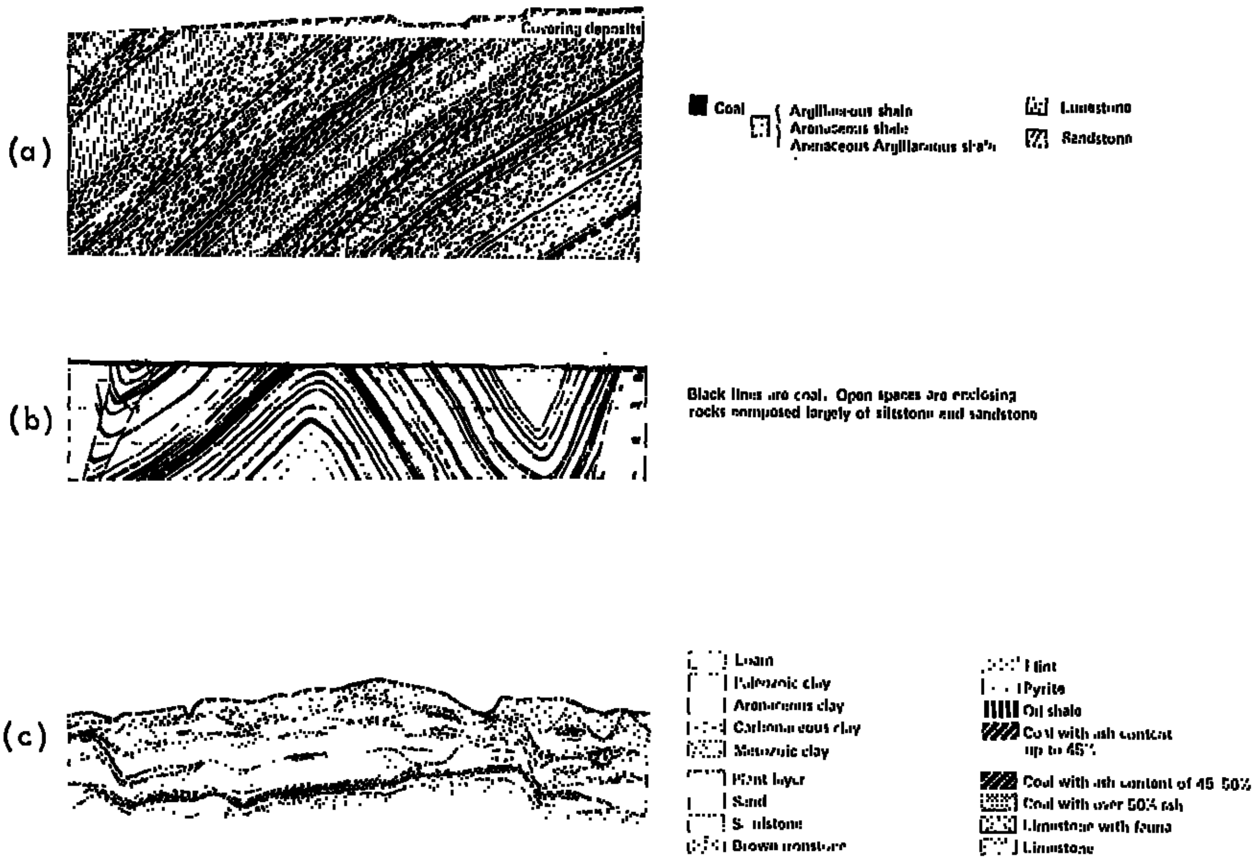
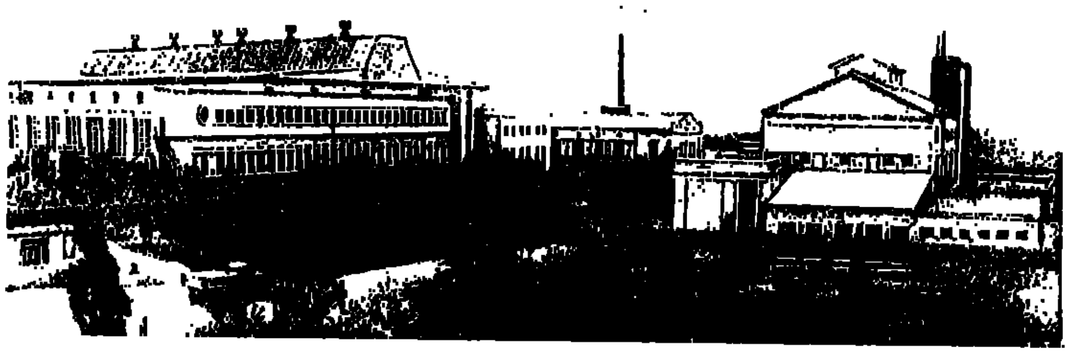


Fig. 4. Geological cross sections of the coal fields at (a) Lisichansk, (b) Yuzhno-Abinsk, and (c) Podmoskovia. We were unable to locate such a cross section for Angren. However, the figure does illustrate the variation in geological conditions addressed by the Soviets.[10]

LISICHANSKAYA PODZEMGAZ STATION



PODMOSKOVNAYA PODZEMGAZ STATION

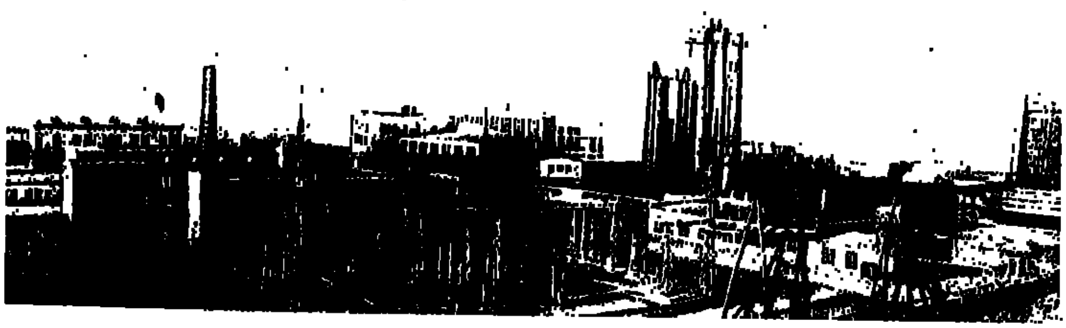


Fig. 5. General views of the gasification stations at Lisichansk and Podmoskovia. The purpose of these photographs is to illustrate the size of the stations, which reflects the size of the Soviet effort.[10]

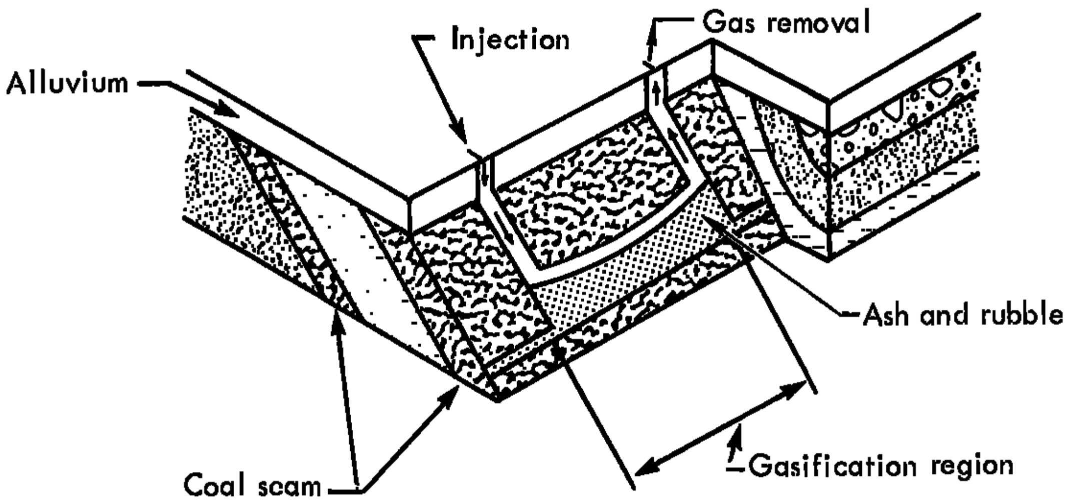


Fig. 6. The Stream Method for gasifying coal in steeply dipping coal beds. This was the first design that the Soviets felt had promise.[14] They tried many schemes in the first few years of their field effort with the intent of transferring surface gasification technology underground.[11] The first attempts involved men underground, using explosive fracturing (the Chamber Method),[10] and excavating or drilling holes from one drift to another (the Borehole-Producer Method). Poor economics and unstable operation led to the abandonment of these methods. The Stream Method was first tested at Lisichansk in 1935[3] in the design shown here. The injection and exhaust holes were drilled along the coal seam and were connected at the bottom by a mined shaft. The flame was initiated in the connecting channel and gradually spread over the entire length. The flow had to be reversed periodically in order to approximate a "horizontal" burn front that moved up the seam. The key feature of this system was that as the coal was consumed, more coal would fall into the void that was created. Thus the coal automatically became rubble and was fed into the combustion zone. This self-forming rubble feature was retained in all further design improvements for both steeply dipping and horizontal coal beds. It might even be considered as a fundamental design requirement for any underground coal gasification system.

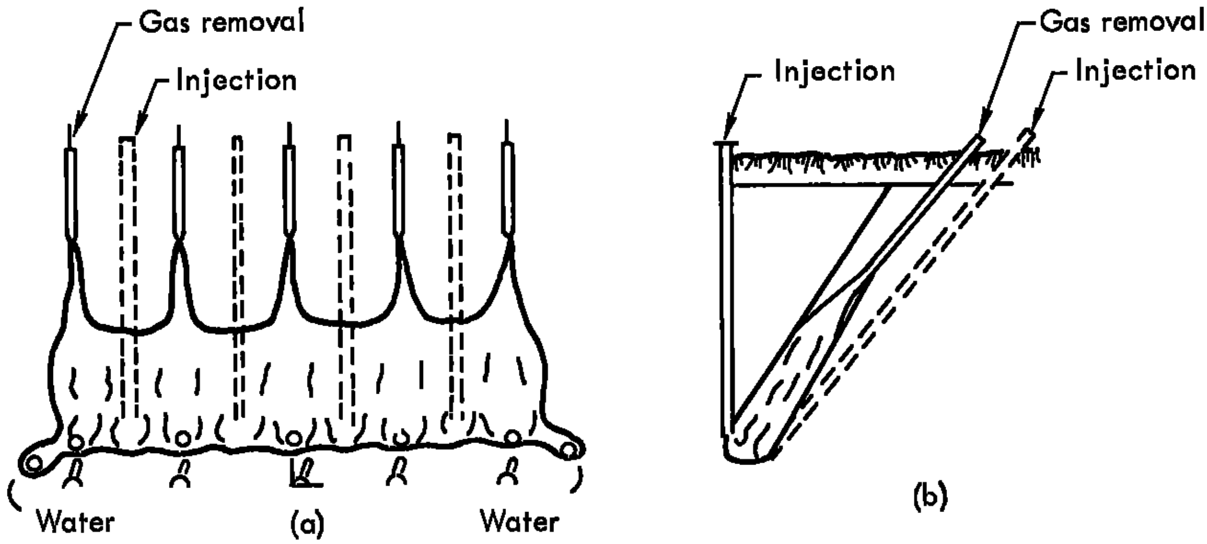


Fig. 7. Typical scheme of an underground gas generator for steeply dipping coal beds. (a) Plan view. (b) End view. It is our interpretation that there were two major problems with the Stream Method presented in Fig. 6 which were resolved in later designs by the modifications presented here. There was a tendency for oxygen (air) to leak through the coal between the two access holes, above the region where combustion was taking place. This would either consume part of the product gas, or would introduce into the gas a hazardous level of oxygen. Also, there was a tendency for the combustion front to channel over the top of coal, resulting in reduced resource recovery and irratic gas quality. In steeply dipping beds these problems were resolved by drilling and casing the air injection holes through the overburden. In this manner the injection holes were isolated from the exhaust holes. Also, the probability of the flame front channeling over sections of coal was minimized by fixing the injection point at the bottom. If the coal seam was thicker than approximately 8 m, it was necessary to drill the injection holes at a slant "under" the seam so that the pipes would not be sheared off by subsidence. However, when these expensive slant holes were used, vertical holes were usually drilled to help in establishing the initial bottom manifold, by hydraulic fracturing or reverse combustion. The vertical holes were also used in the first stages of gasification. (All mining was eliminated for humanitarian and economic reasons.[11,15])

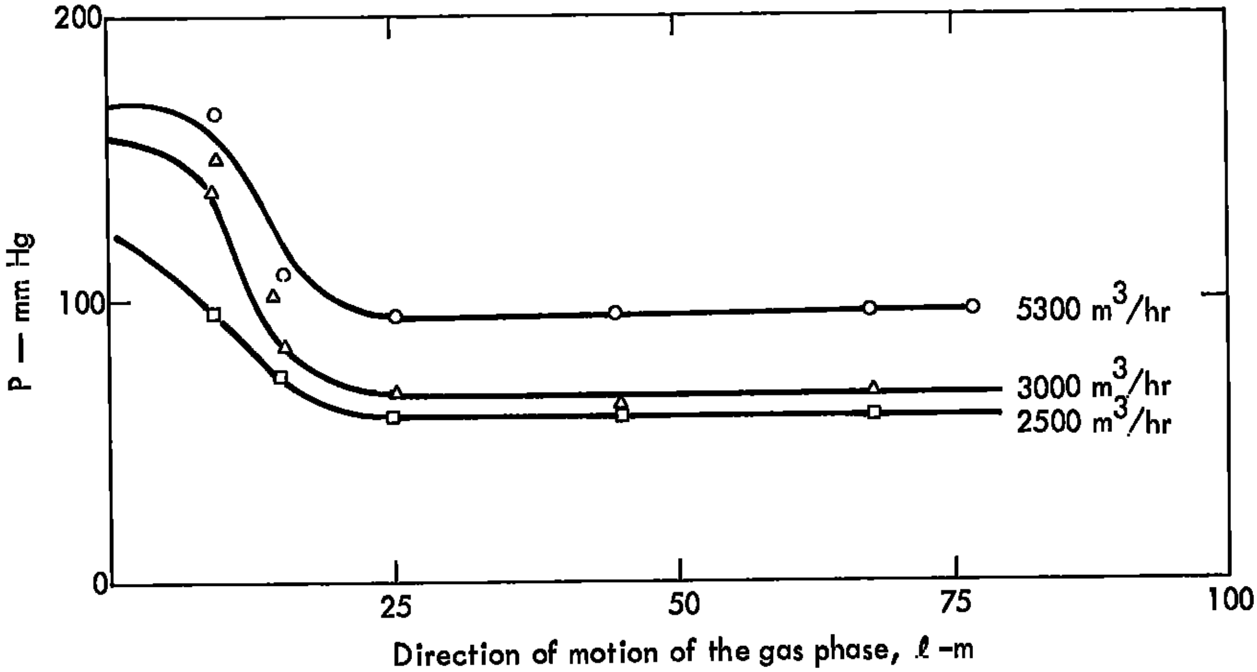


Fig. 8. Change in pressure, P, of the gas phase along the channel length, l, of gas generator No. 1 of Yuzhno-Abinskaya station. The values 2500, 3000, and 5300 m^3/hr are injection rates of the blast. This figure illustrates that most of the pressure drop was often observed to occur in the lower regions, near the injection point in the region of the flame front. There are a number of contributing factors that would cause this. Two important ones are the following. (1) There is a gas expansion at the flame front due to both the increase in temperature and the increase in molar quantity. (2) The subsiding roof could have a low permeability and thus restrict the gas flow. If the second phenomenon was an important contributor. It could not only cause a problem by restricting flow in a one-dimensional sense, but it could also cause severe two-dimensional flow distortion problems. This two-dimensional redirection of flow over a long distance up the seam would eventually cause the loss of too much control over the direction of the gas flow, resulting in poor resource recovery. For these reasons an additional modification was introduced, as shown in Fig. 9 [10]

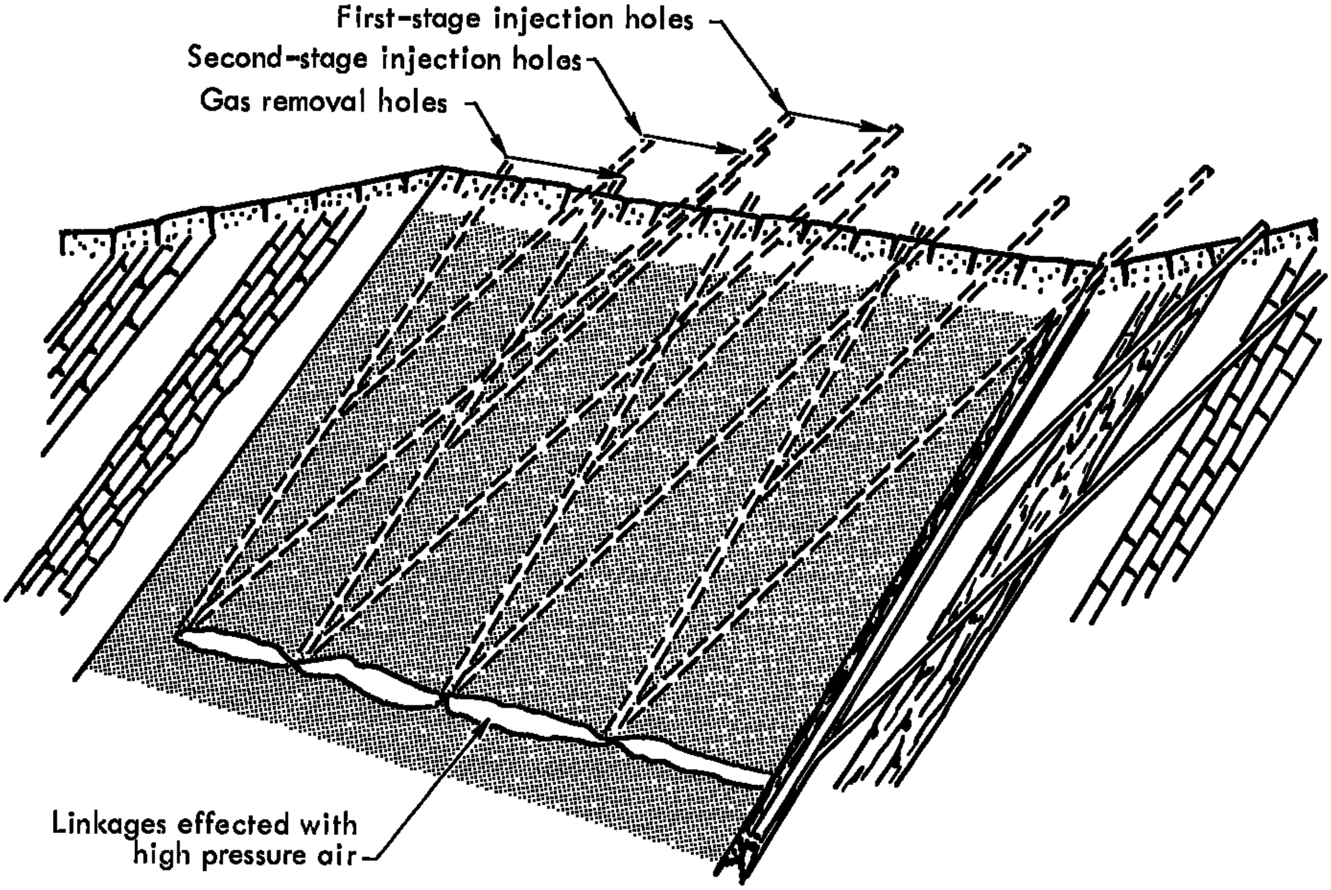


Fig. 9. Preparation of steeply sloping seam at Yushno-Abinsk. The Soviets drilled a number of air injection holes spaced along a gas production hole to overcome the high flow resistance and flow distribution problems associated with roof collapse.[5]

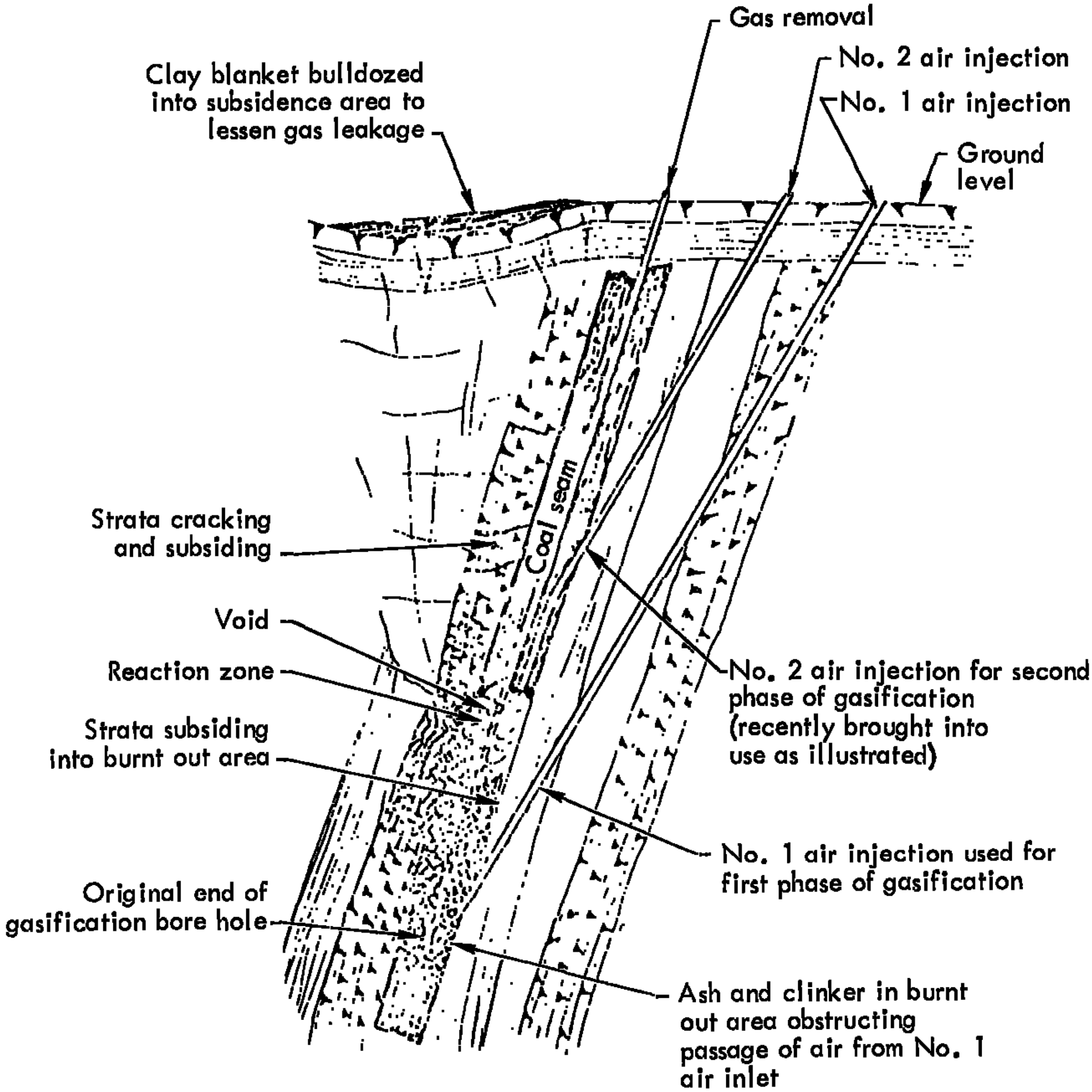


Fig. 10. Use of two air injection holes in a steeply sloping seam. The Soviets commonly encountered severe gas leakage to the surface through cracks created by subsidence. This figure shows part of the solution employed to solve this problem, which was to bulldoze clay into the cracks that reached the surface.[5] In addition, the system was operated at the lowest possible pressure consistent with required production flow rates (injection pressure about 3 atm).[11]

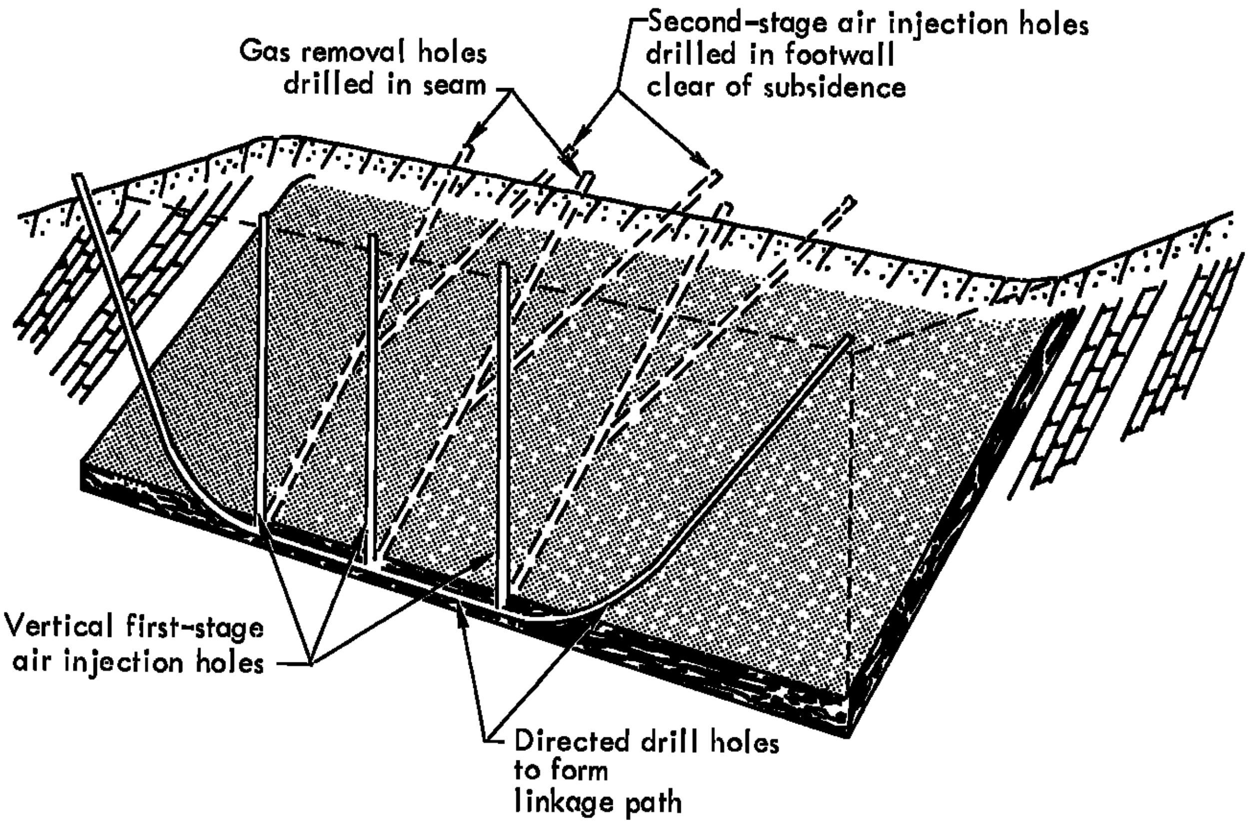


Fig. 11. Alternative layout using directed drillholes for linkage. The Soviets often formed the bottom manifold between gas injection and production holes using directional drilling. This scheme for steeply dipping beds was first developed at Lisichansk in 1955.[5,11,16]

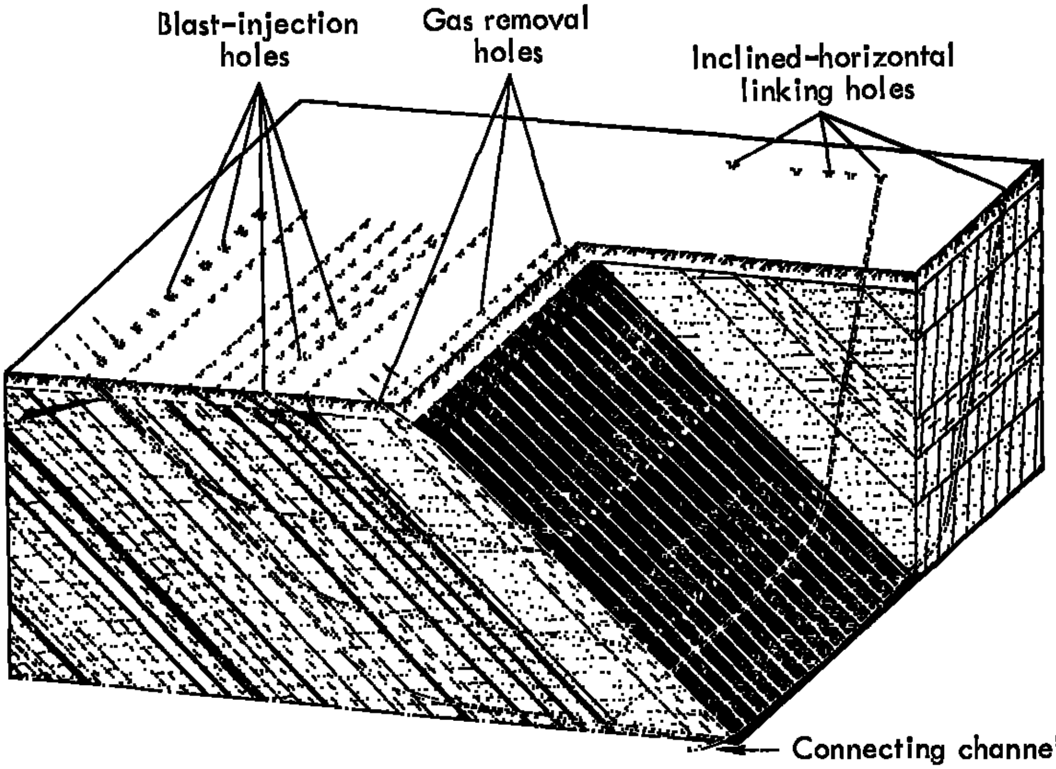


Fig. 12. One of the schemes of equipping an industrial-type gas generator in a suite of steeply dipping coal seams. This figure presents a pictorial view of a Soviet proposal for gasifying several steeply dipping coal seams simultaneously using a common set of gas injection pipes. It is not clear that this was ever implemented. The operating sequence consists of first igniting at the intersection of the bottom row of blast injection* holes and the coal seam farthest from where the blast pipes emerge from the surface. This coal seam is processed until the flame front reaches the next highest row of blast injection holes, at which point the next higher row of blast holes is used to supply blast to the seam. At the same time the bottom blast holes are plugged between this first coal seam and the next one to be gasified, which is one step closer to where the blast injection holes intersect the surface. These bottom injection holes are then explosively opened to the second seam, and gasification of that seam is initiated. This sequence can be continued in an obvious manner until all the coal seams intersected by the blast injection holes are gasified.[10]

*Blast injection is used here as it appears in the Soviet literature. It refers to the process of injecting oxygen-bearing gas (usually air) into the combustion region.

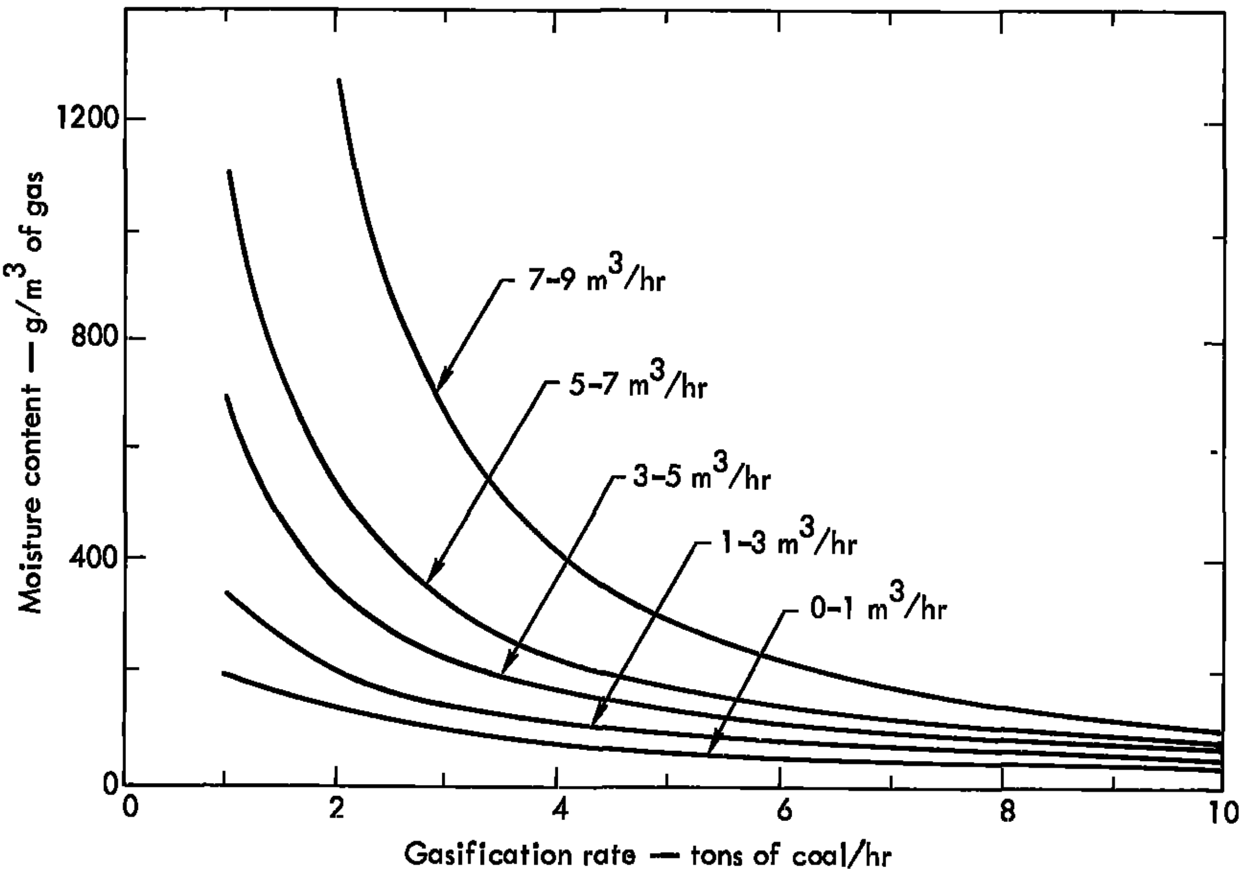


Fig. 13. Moisture content of the gas as a function of the gasification rate of the coal seam. The operating data that will be presented in the following five figures were taken at the Yuzhno Abinskaya station. However, the functional relationships represented in the graphs are typical of both steeply dipping and horizontal coal bed gasification. Note in this figure that as the gasification rate is increased, the moisture content in the product gas decreases. This is to be expected since the moisture is primarily due to the underground water intrusion rate which is essentially constant at any particular point. The balancing of the gasification rate against the moisture intrusion rate has a significant effect on the heating value of the product gas, as will be seen in the following figures.[17]

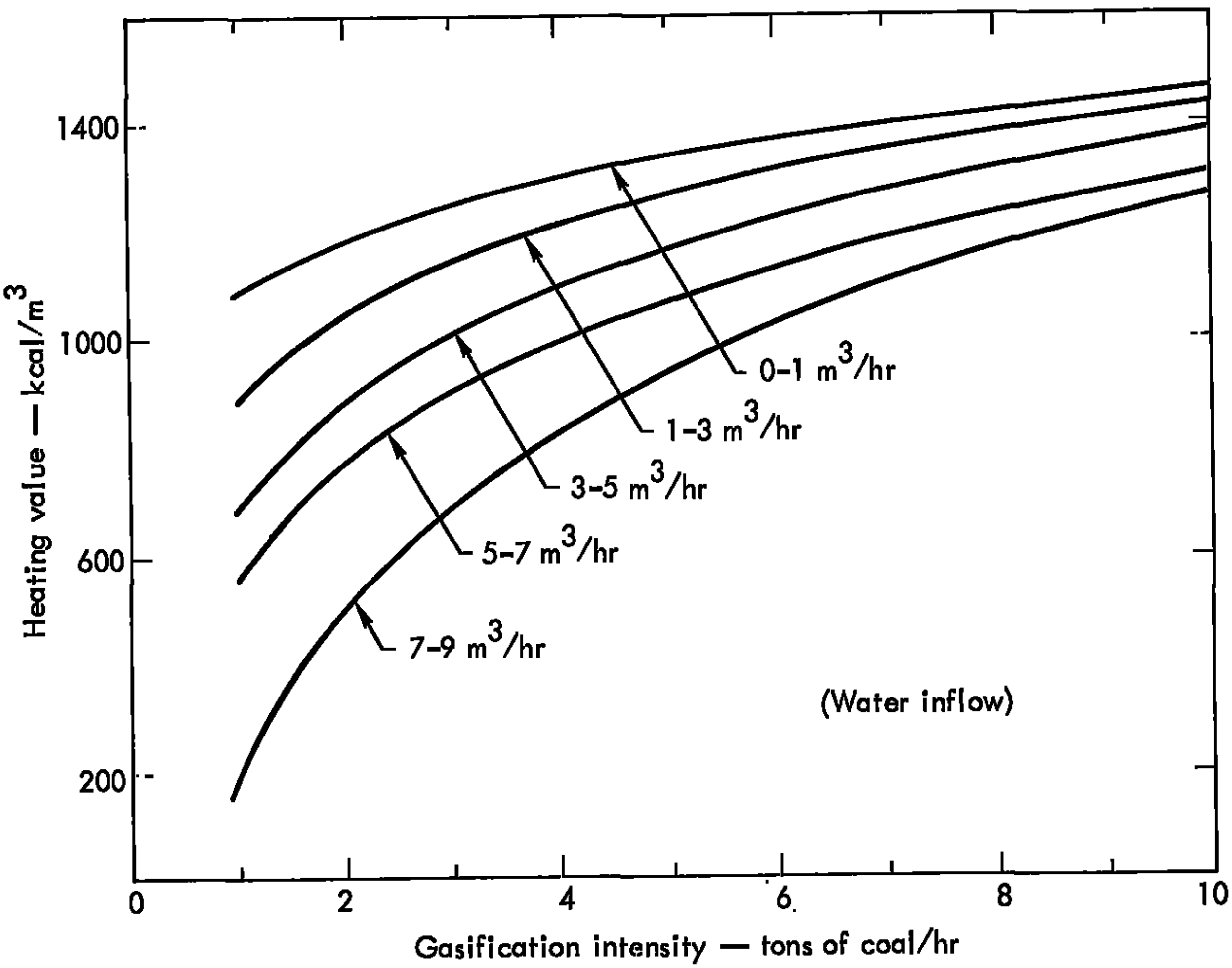


Fig. 14. Effect of gasification intensity on the calorific value of the gas at various water inflow rates into the gasification zones. This figure illustrates the effect of gasification intensity on the heating value of the product gas for various water inflow rates. The data show that the heating value always increased with increased gasification intensity and reduced water inflow rate. In theory there is actually an optimum water intrusion rate for any given blast injection rate. In practice, this was generally unimportant to the Soviets since they usually had higher water intrusion rates than desirable, forcing them to operate on the water-rich side of the optimum.[10,17]

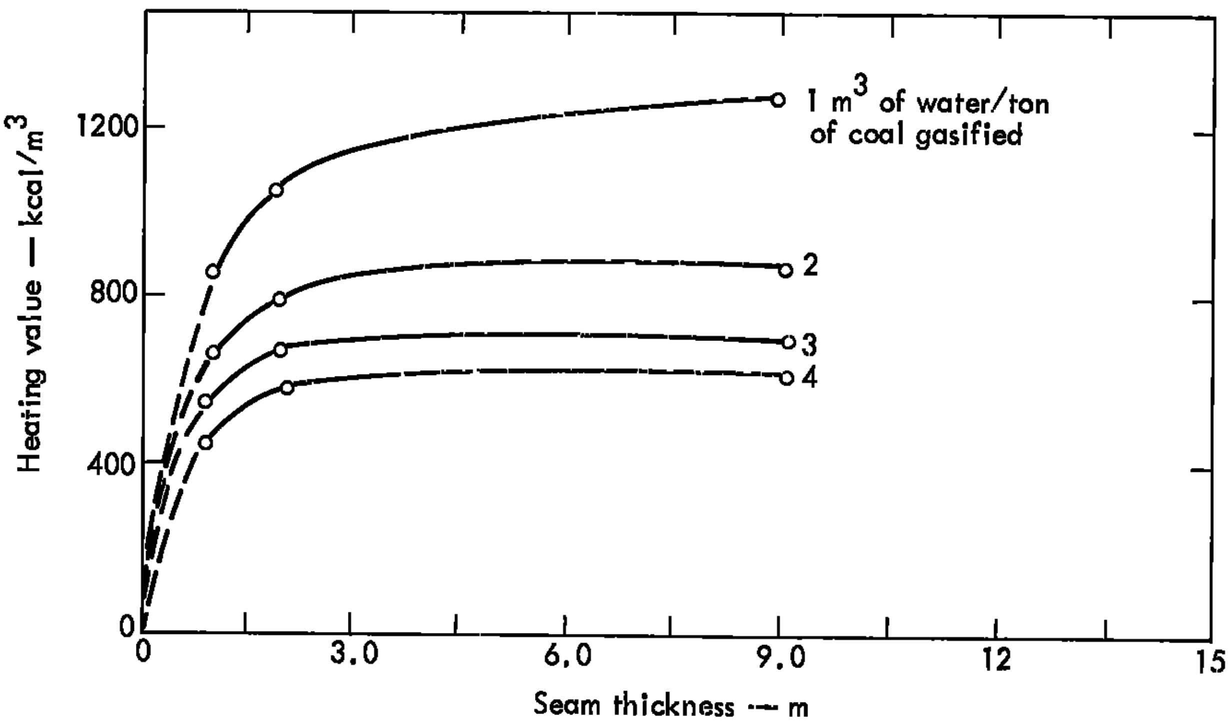


Fig. 15. Effect of seam thickness and the specific water inflow into gasification zones on the calorific value of gas obtained by underground gasification. Both water intrusion rate and coal seam thickness can have a strong effect on the heating value of the product gas. The effect of the water intrusion rate was discussed earlier, but this figure also illustrates the effect of seam thickness. It can be seen that the heating value of the product gas falls off dramatically as the coal seam gets thinner than 1 to 2 m. This is due to thinner seams losing a larger fraction of heat to the surrounding formation. The higher heat losses result in lower flame front temperatures, which in turn shifts the CO/CO_2 equilibrium towards the production of more CO_2. The 1- to 2-m limitation in coal seam thickness has very important implications. Most of the coal in the eastern part of the U.S. lies in seams less than 2 m thick, while most of the coal in the western U.S. is in thicker seams.[17]

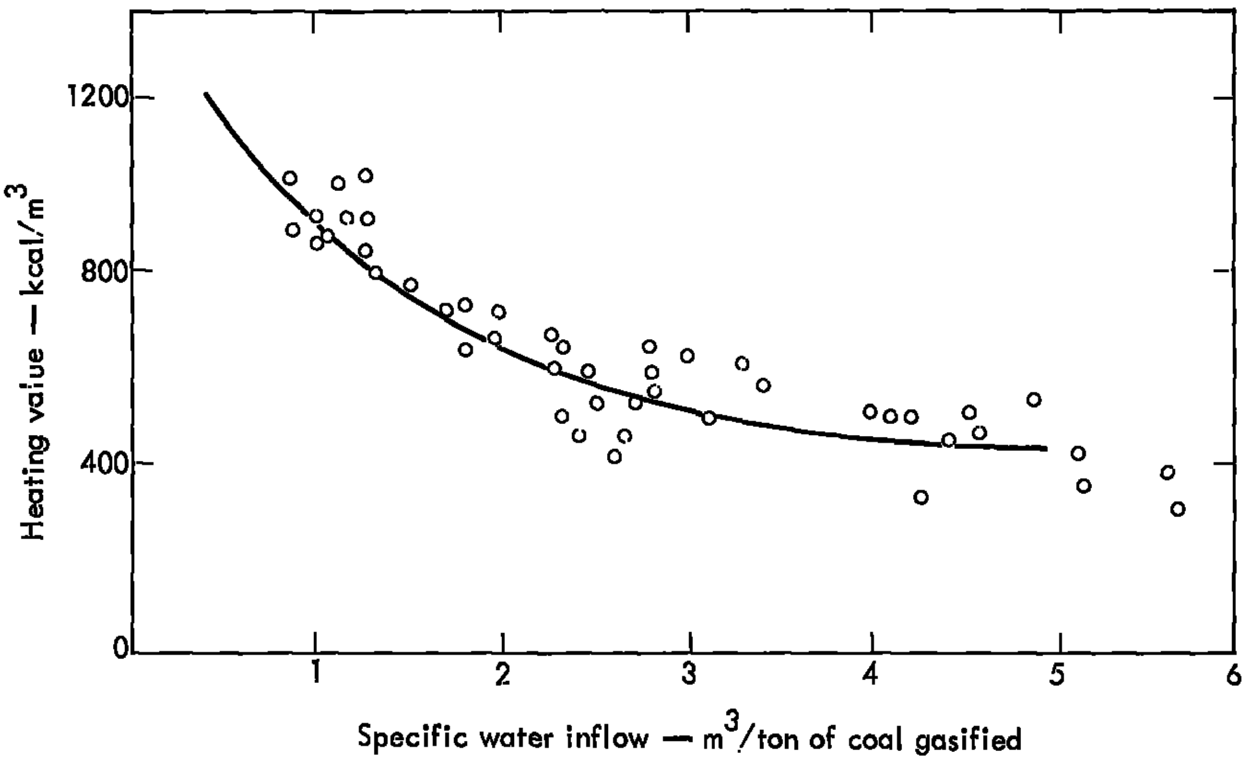


Fig. 16. Calorific value of the gas as a function of its moisture content. This figure shows the heating value of the product gas vs specific water inflow.[17] This figure and the following one should have an optimum at approximately 0.5 m^3/ton of coal gasified.[18] (In practice, this number varies considerably between coal seams[19] and varies according to whether the water intrusion is upstream or downstream from the fire front.) The optimum does not appear in these data because the Soviets usually operated in a region where there was more water inflow than desirable. The reason for the optimum is as follows. With no water intrusion, a great deal of the combustion energy goes into heating the nitrogen in the air blast. When a little water is added, it increases the heating value of the product gas by converting some of the energy in the hot nitrogen into a combustible product by the endothermic reaction: $H_2O + C = CO - H_2$. However, as more water is added, the cooling effect of the water will eventually reduce the flame temperature, which in turn will shift the CO_2/CO distribution towards the production of more CO_2. This will clearly reduce the heating value of the product gas.

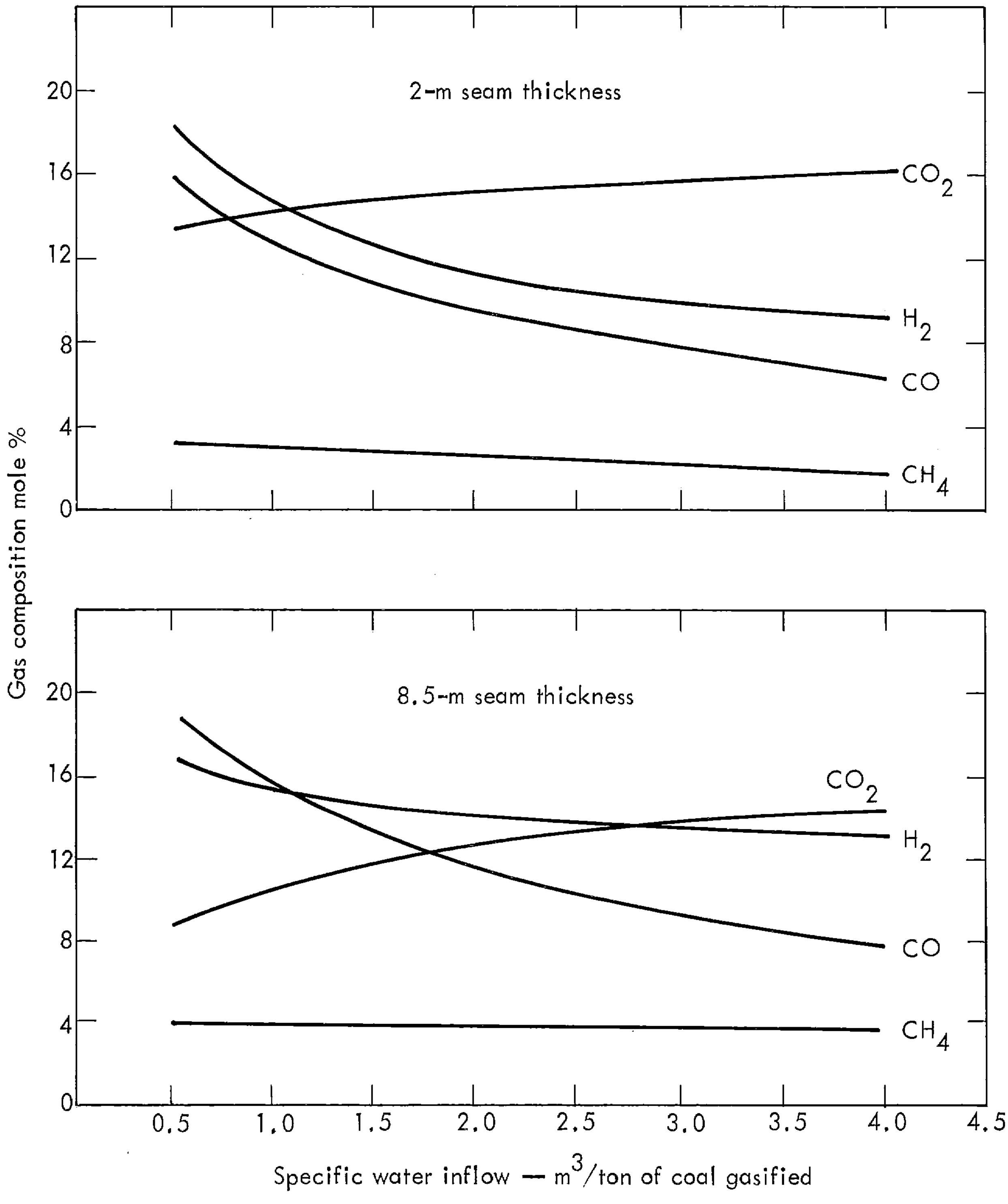


Fig. 17. Effect of the specific inflow rate of water into the gasification zones on the chemical composition of gas obtained by underground coal gasification. It can be seen that the CO_2 fraction increases both with water inflow rate as well as with decreasing seam thickness. Both are consistent with a cooler flame front shifting the CO_2/CO equilibrium towards an increase in the CO_2 fraction.[17]

Month — year	Hourly mean air flow (m^3/h)	Heat content of gas ($kcal/m^3$)
Nov. — 1962	3460	1280
Dec. — 1962	7000	1304
Jan. — 1963	8030	1291
Feb. — 1963	8760	1260
Mar. — 1963	8400	1264
Apr. — 1963	9850	1238
Average	7600	1260

Fig. 18. Mean air flow and heat content by months for gas generator No. 5a-b. This table shows the stability of product gas heating value that was achieved over a 6-mo period. The blast flow rate was used as a means of controlling the heating value at Yuzhno-Abinsk.[20]

Calorific value of the gas Q = 1300, to 1196 kcal/m^3.
Gas leakage = 10%.
Gas water content = 290 g/m^3.
Relative blast intensity = 17 m^3/hr - m^{-2}.

1. Heat of combustion of the dry gas = 69.9%,
2. Heat of combustion of leakage gas = 7.8%,
3. Heat content of the gas = 4.2%,
4. Heat content of leakage gas = 0.5%,
5. Heat content of water in the gas = 9.2%,
6. Heat content of the humidity in gas leakage = 1%,
7. Heat content of the ash residue = 0.1%,
8. Losses to the surrounding medium = 7.3%,
9. Heat content of the dry coal
10. Heat content of water in the coal
11. Heat content of dry air blast

$\left.\begin{array}{l}9.\\10.\\11.\end{array}\right\} = 0.1\%$

12. Heat content of water introduced = 0.5%.

Fig. 19. Thermal balance of the gasification process in generator No. 5a-b in seam IV interior (9 m thick) at Yuzhno-Abinsk, January 12-31, 1961. This figure gives a breakdown of where the energy in the coal went for one particular generator. It can be seen that 70% of the heating value of the coal was recovered as heating value in the gas.[20]

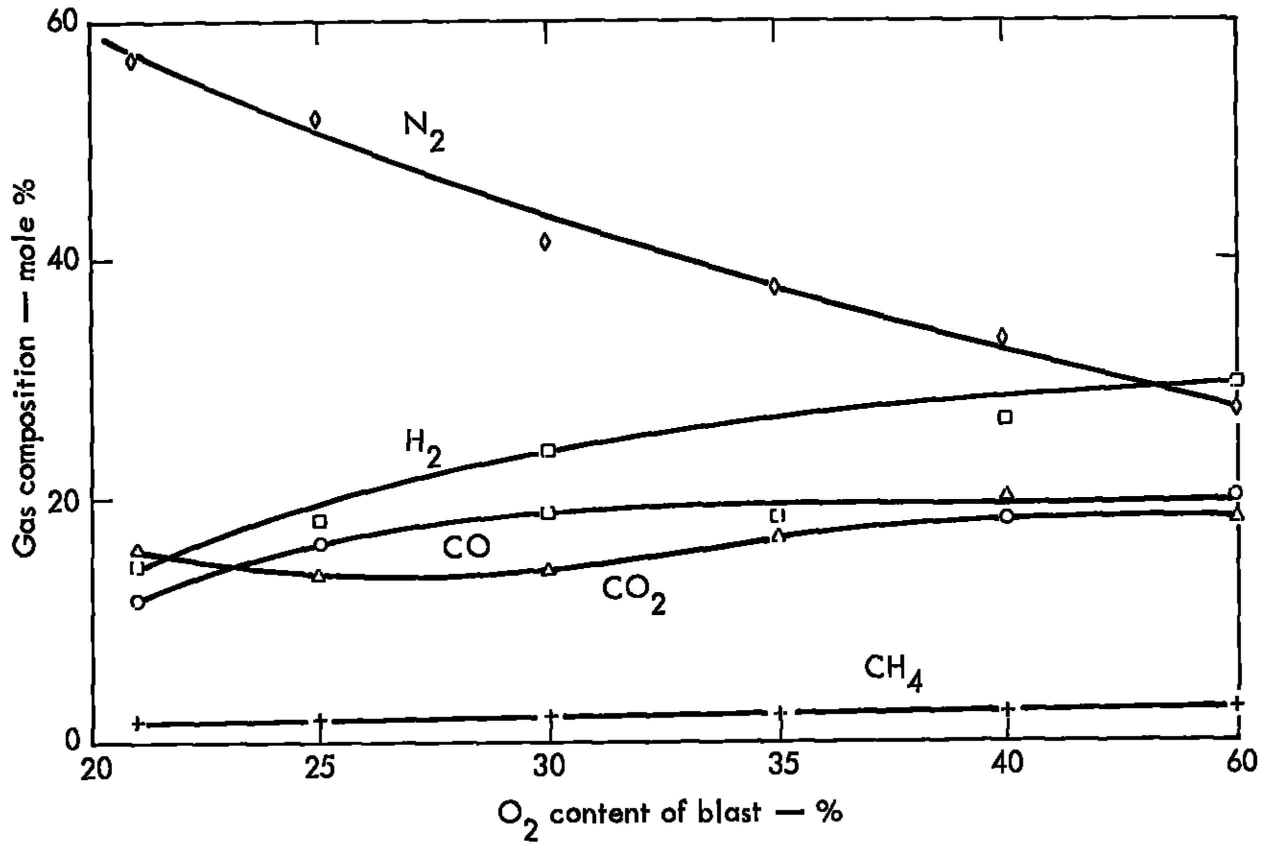


Fig. 20. Change in the gas composition with increasing oxygen content of the blast, on the basis of operation of underground gas generator No. 1 of Gorlovskaya Podzemgaz station. The Soviets experimented extensively with enriching the air blast with oxygen; some results from Podmoskovia are presented here. Similar experiments at Lisichansk showed significantly different product gas concentrations, because "conditions of operation of the gasification channels" were different.[10] One interesting point is that the CO_2/CO ratio did not change significantly with increasing oxygen concentration in the blast. Since the combustion zone would be hotter with increased O_2 concentration in the blast, the insensitivity of the CO_2/CO ratio would have to be explained by reactions taking place in the cooler zones further downstream. The product gas composition is probably dominated by the shift reaction, $CO + H_2O = CO_2 + H_2$. This is consistent with the increasing H_2 concentration.

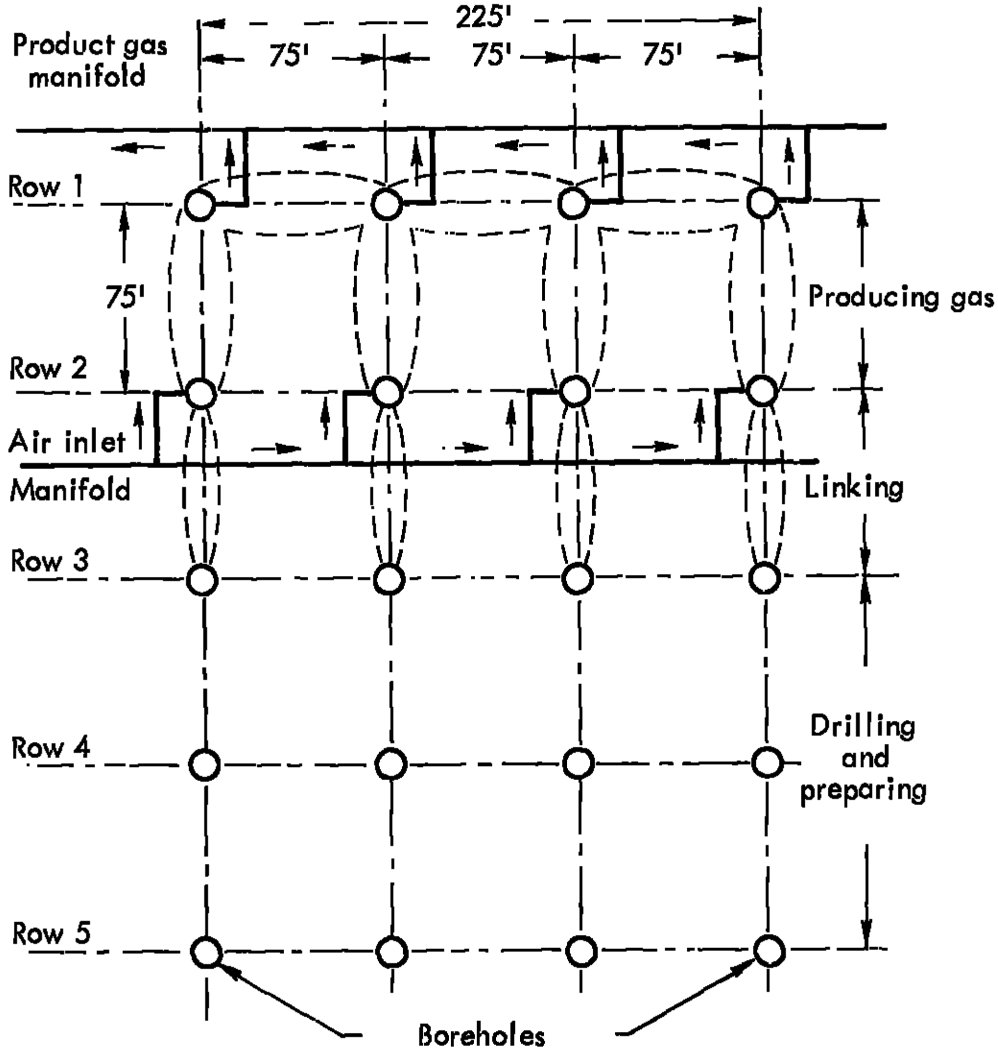


Fig. 21. Plan of a shaftless generator for a plant in the Moscow region. The following nine figures will deal with the Soviet experience in processing horizontal coal seams. This figure shows a typical plan view of the Soviet process. The dotted lines are meant to show the location of the underground linkage channels formed in the coal by a countercurrent combustion step in preparation for gasification. The production phase of gasification is carried out by cocurrent combustion in the channels. Cocurrent and countercurrent refer to the flame front propagating in the same or opposite direction as the gas flow, respectively.[5,21]

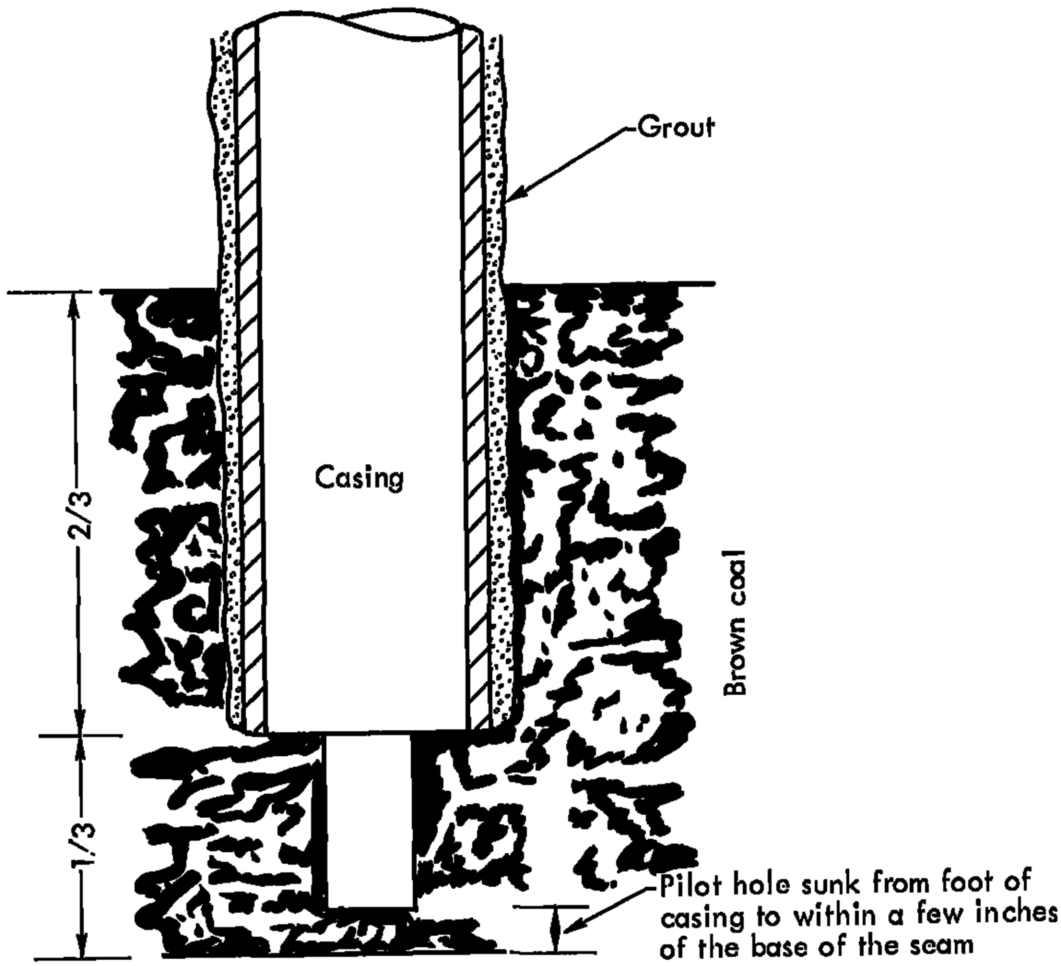
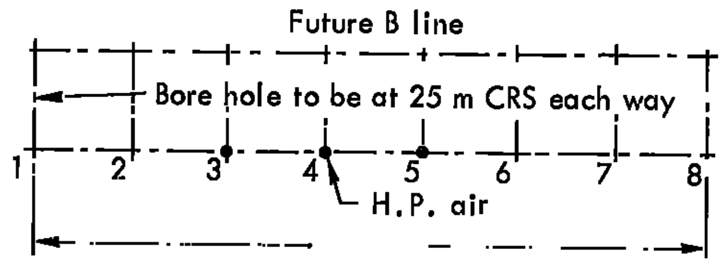
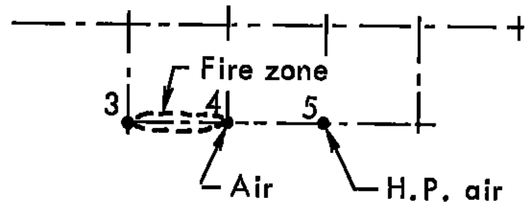


Fig. 22. Arrangement at foot of boreholes for air linkage in brown coal. For horizontal coal beds it was important to complete and cement the access pipes two-thirds of the way through the seam. This was done to insure that the initial linkage channel, formed by countercurrent combustion, was confined to the bottom of the seam. This was very important, because the Soviets found that only the coal above the linkage channel was consumed during the process.[5]

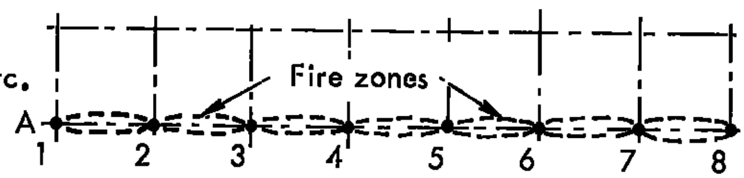
Stage I
Drill holes 3,4 & 5 in 'A' line. Apply H.P. air to A.4. Establish link to (say) A.3.



Stage II
Ignite A.3 as induce fire zone in line A.3 - A.4. Apply H.P. air to A.5 to link to A.4.



Stage III
Link and induce fire zones A.2 -A.3, A.6-A.5, A.1-A.2, etc.



Stage IV
Start drilling and linking line B1, B.2, etc., to line 'A' holes.

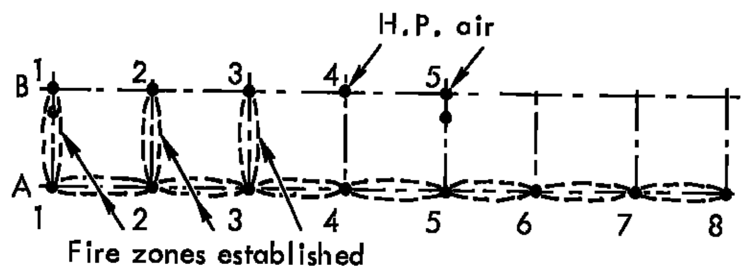
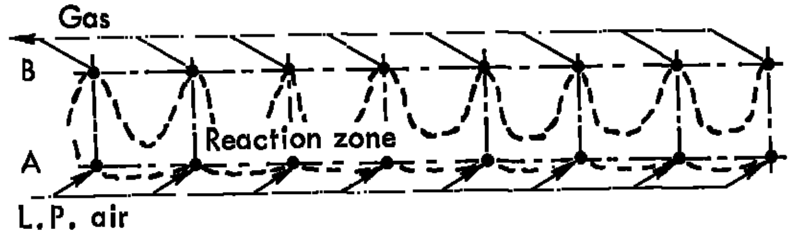


Fig. 23. Initial stages of linkage and gasification in brown coal. This figure presents the first sequence of steps using reverse combustion for preparing a coal bed for gasification.[5]

Stage V
Start gasification L.P. air to A.1, A.2, etc., gas from B.1, B.2, etc.



Stage VI
Drill hole in line 'C', link to line 'B' progressively as gasification proceeds.

Later
Supply air to 'B' line.
Take gas from line.
(All 'A' holes capped.)

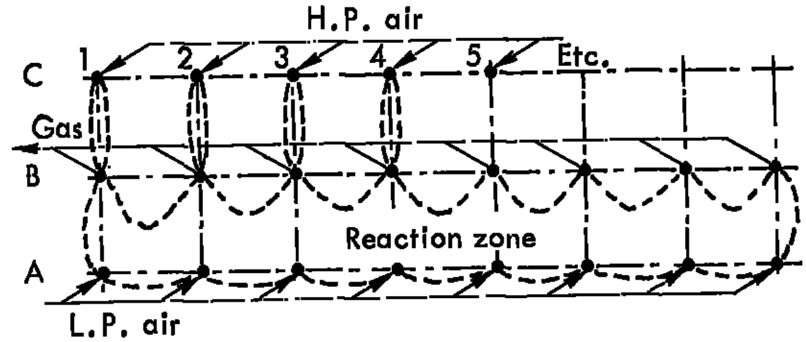


Fig. 24. Concluding stages of linkage and gasification in brown coal. This figure presents the simplest method of completing the preparation and carrying out the following cocurrent combustion gasification.[5]

Stage V
After linking 'B' holes to 'A' proceed to link 'C' holes to 'B' before starting gasification.

Stage VI
Start gasification with L.P. air to 'A' holes taking gas from 'C' holes, 'B' holes being capped.

Stage VII
During stage VI link holes D1-D8 to line 'C'. When gas from 'C' deteriorates move air supply to 'B' holes and draw gas from 'D' and 'A' holes.

Later
When gas from 'A' holes becomes unusable, cap 'A' holes. Draw gas from 'D' and prepare line 'E' etc.

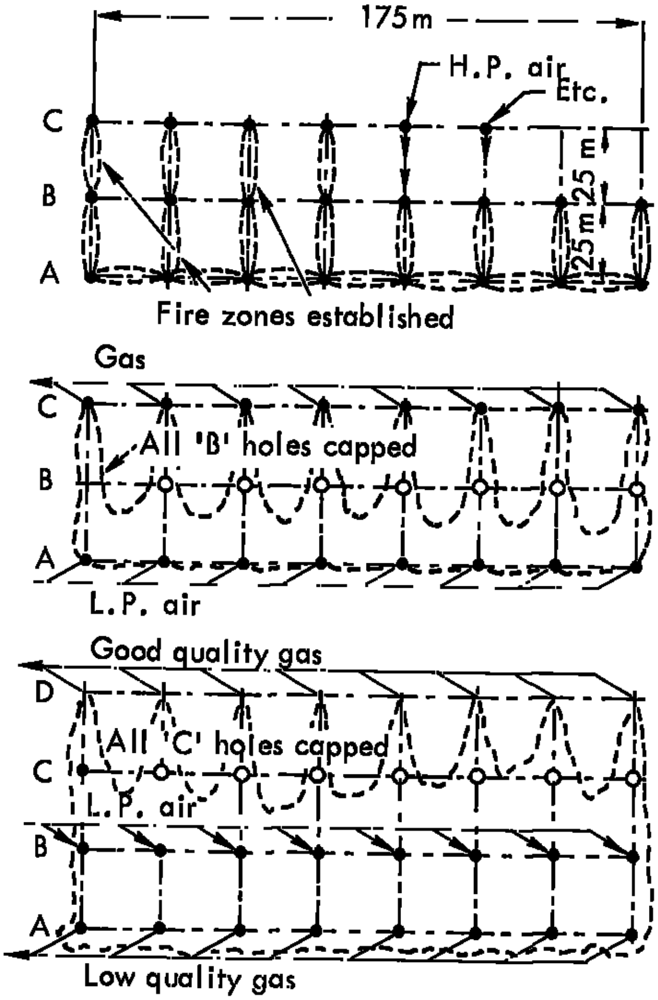


Fig. 25. Modified concluding stages for improved gasification in brown coal. This figure presents an alternate, more complex, mode of carrying out the cocurrent combustion gasification as well as further counter-current combustion linking. In this case two qualities of product gas are produced, with the two being combined to give an acceptable quality gas.[5]

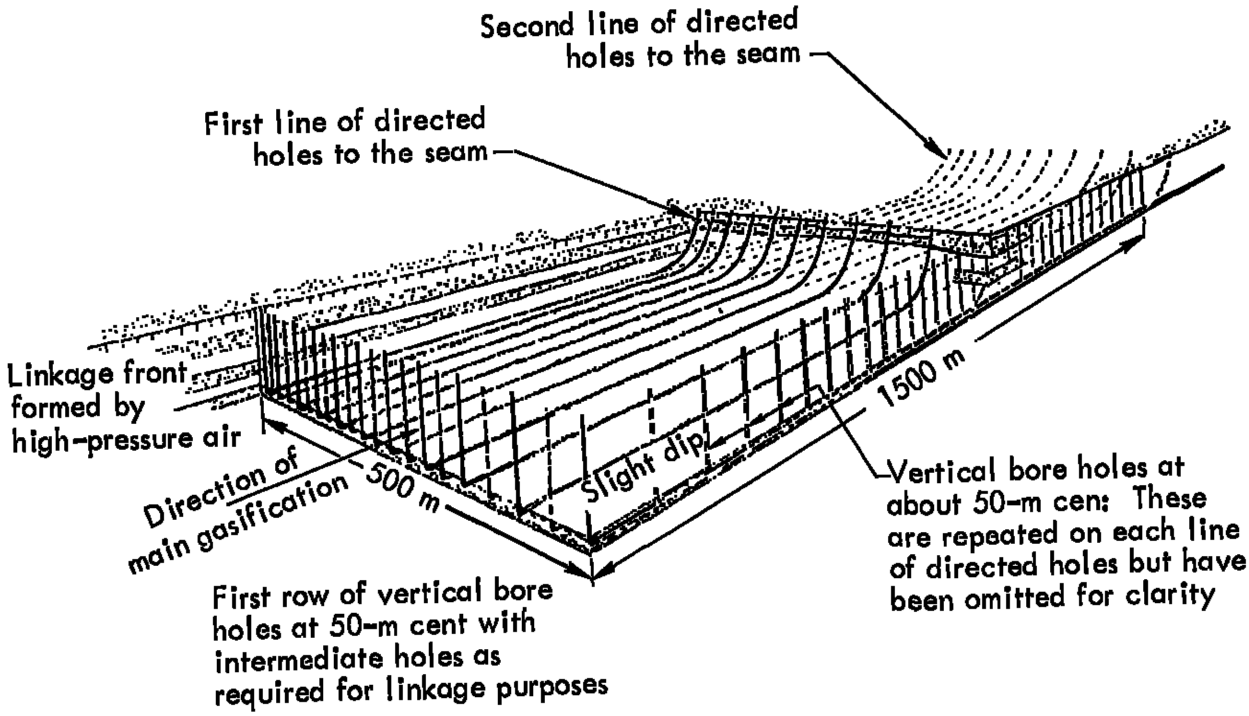


Fig. 26. Proposed method of development in the near-level seams at Kholmogorsk. The Soviets used directional drilling as well as of countercurrent combustion to establish a linkage path at the bottom of the coal seam. This figure illustrates one such proposed system. However, even though the Soviets did use directional drilling for this purpose, it is not clear that they were ever able to achieve the very long extensions of the holes along the bottom of the coal seam that are shown in this figure.[5]

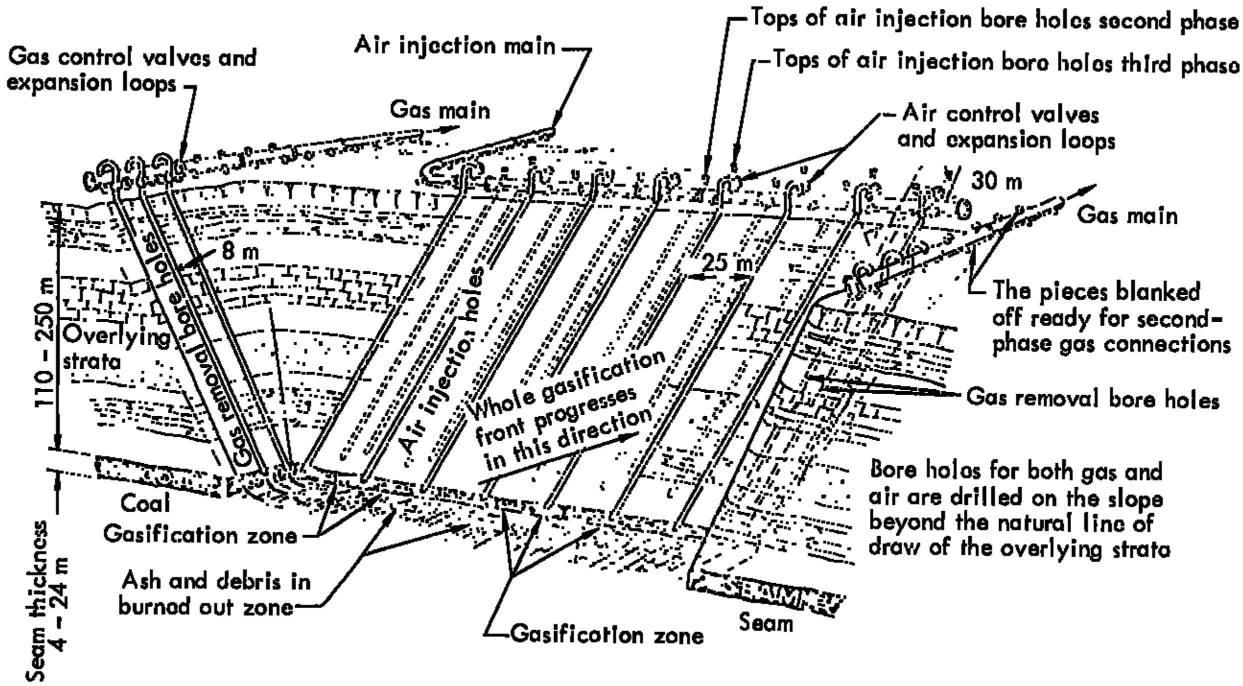


Fig. 27. Projected layout of boreholes at Angren to suit thick brown coal and heavy subsidence. This figure shows how the drilling pattern and operational method were modified to accommodate thick coal seams. The primary problem to be solved was that with thick seams, the ground subsidence had a tendency to shear off the access pipes prematurely. To resolve this, two modifications were made. (1) A lateral withdrawal/injection technique was developed.* In this method, one of the two functions (gas withdrawal or injection) was performed by a row of pipes along the side of the zone being gasified. The remaining function was accomplished with a rectangular pattern of pipes entering the seam directly over the coal to be gasified. (2) Within the framework of this general pattern, all pipes were drilled on a slant to keep them out of the subsidence region during their functioning lifetime. When gasification is carried out in this manner it can be seen that the row of pipes along the side of the zone being gasified is never affected by subsidence, and the pipes in the pattern directly over the coal being gasified are not affected until after they are no longer needed. Therefore, with this design one is never attempting to operate with a pipe that has been exposed to any ground movement due to subsidence.[5] This design also has the additional advantage of adding a cross-flow component to the gas flow which will help to recover mounds of coal that might otherwise be left between channels.

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*Lateral withdrawal/injection is complex, and no attempt to describe this process will be made here.

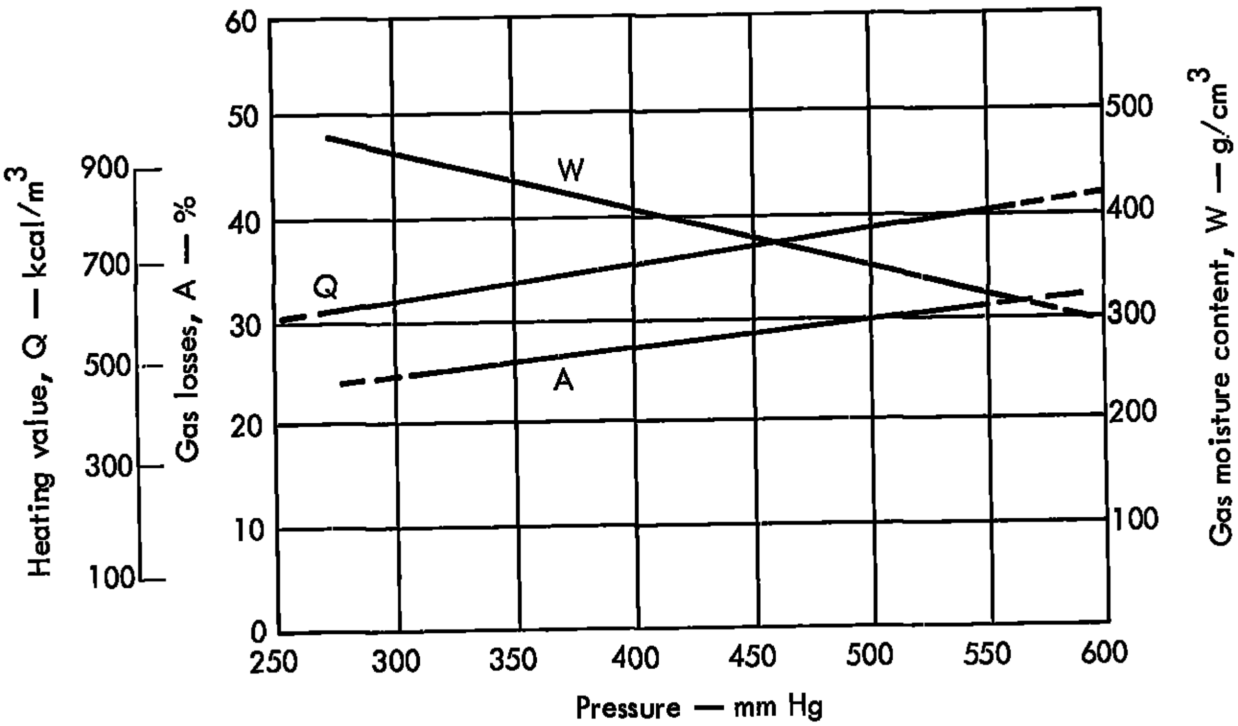

Fig. 28. Change in the moisture content, w; heating value, Q; and losses of the gas, A as a function of the pressure, P, in the gas phase of the gasification channel, on the basis of operation of underground gas generators at Podmoskovnaya station. Gas loss data for the Podmoskovnaya station are presented in this figure.[10] At the usual operating pressure (3 atm or less) the gas loss at Yuzhno-Abinsk was about one-half and the loss at Angren[7] about one-third that at Podmoskovnaya. Since the loss increases as the square of the pressure, a system should always be operated at the lowest possible pressure consistent with throughput. This was one of the more important requirements that necessitated the construction of the highly permeable linkage channels in preparation for gasification. If the channels did not have a sufficiently high permeability, the pressure required to achieve the necessary high gas flow rates would rise, and the resulting gas losses would increase. Operation at low pressure has the additional advantage of being able to use relatively inexpensive blowers to supply the air. The figure also shows a moderate improvement of the heating value of the gas with pressure. This is easily understood in terms of the gas pressure reducing the water inflow rate, which is also shown.

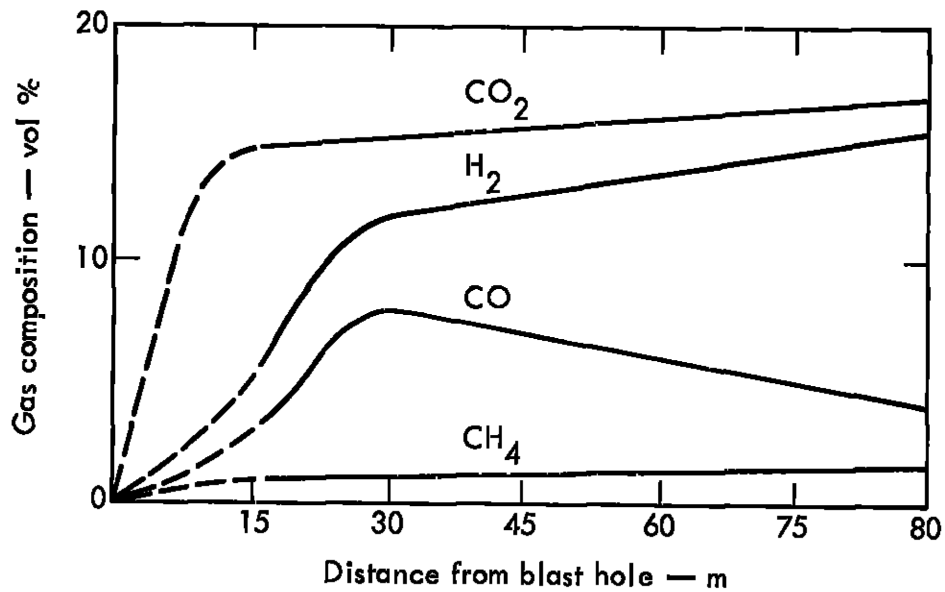

Fig. 29. Change in gas composition along the length of the gasification channel. The gas composition can change continuously as it progresses along a channel. This figure shows composition changes that were frequently observed at Podnoskovia.[10] It can be seen that CO_2 is formed early, CO is then formed by the reduction of CO_2 as well as directly, and finally the CO concentration falls off while the H_2 and CO_2 concentrations build up. It is believed that this last stage is due primarily to the "shift" reaction, $CO + H_2O \rightarrow CO_2 + H_2$. It is not generally desirable to allow this reaction to take place since it reduces the heating value of the product gas. The Soviets thought that this reaction was catalyzed by materials in the ash and rock. They also believed it to be dependent on the coal type.[7]

Reactions apparently continue to take place all along the channel length. At Angren the heating value increased with channel length up to 250 m, the maximum used. This could only happen if the channel remains relatively hot along its entire length. This hot channel is a necessary, critical feature of the Soviet design in terms of controlling the effects of liquids. Large amounts of liquids are generated both from water intrusion from the surrounding formation as well as from the pyrolysis of the coal. If the liquids are allowed to condense in the gasification channel, there would be more than enough liquids to severely plug the channel to gas flow.[22] It is therefore essential to keep the lowest temperature in both the channel and the exhaust pipe above the condensation temperature of both the water and pyrolysis tars in the product gas. Some work by the Soviets indicates that this lowest permissible temperature is approximately 150°C.[11]

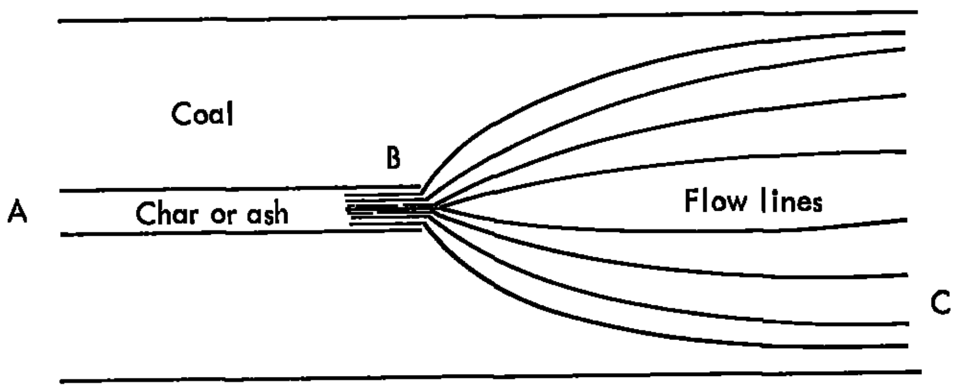

Fig. 30. Channel formation for cocurrent vs countercurrent burns. Some features of the linking procedures will be discussed in the following nine figures. This figure is useful for explaining some of the observed differences between cocurrent and countercurrent burns. Consider the idealized case presented in the figure where there is a narrow, highly permeable channel of char or ash extending into a coal seam with much lower permeability. If we were to draw flow lines for such a media, where flow is either from A to C or C to A, it is easy to see that they would converge at the tip of the channel such that in the region from A to B, the majority of the gas flow would be carried by the channel, and from B to C, the gas flow would distribute more uniformly across the bed, independent of flow direction. If the coal is ignited in the channel in the region of B, and if the flow direction is C to A (countercurrent combustion), it can be seen that the flame front at the tip of the channel, at B, will see a much larger supply of oxygen than the walls of the channel further towards A. Therefore, as the flame front at the tip progresses towards C, the oxygen-starved channel walls will not move out significantly. The result is that this form of countercurrent combustion creates a channel with a relatively small and constant diameter. In contrast, if the flow direction is from A to C (cocurrent combustion), the channel walls will be exposed to a large flow of oxygen, which will support combustion on the walls and thus promote a widening of the channel. This is a simplified explanation of why countercurrent burns form small diameter channels, while the following cocurrent burns are observed to progress with a relatively broad front. In addition, a countercurrent burn is not subject to plugging due to coal swelling or the presence of a condensing liquid front downstream from the flame front, whereas a cocurrent burn is very vulnerable to such plugging. For these reasons, a countercurrent burn is ideally suited for forming highly permeable channels in a coal seam as a preparatory step, but it can not be used for gasification in the process phase, since it results in very poor resource utilization. In contrast, a cocurrent burn can not be used to form initial gasification channels due to plugging, but it can be used in the process phase because of its high resource use. Therefore, in a gasification process both countercurrent and cocurrent burns are used with the countercurrent burn used to prepare the bed, and the cocurrent burn to carry out the gasification.[10]

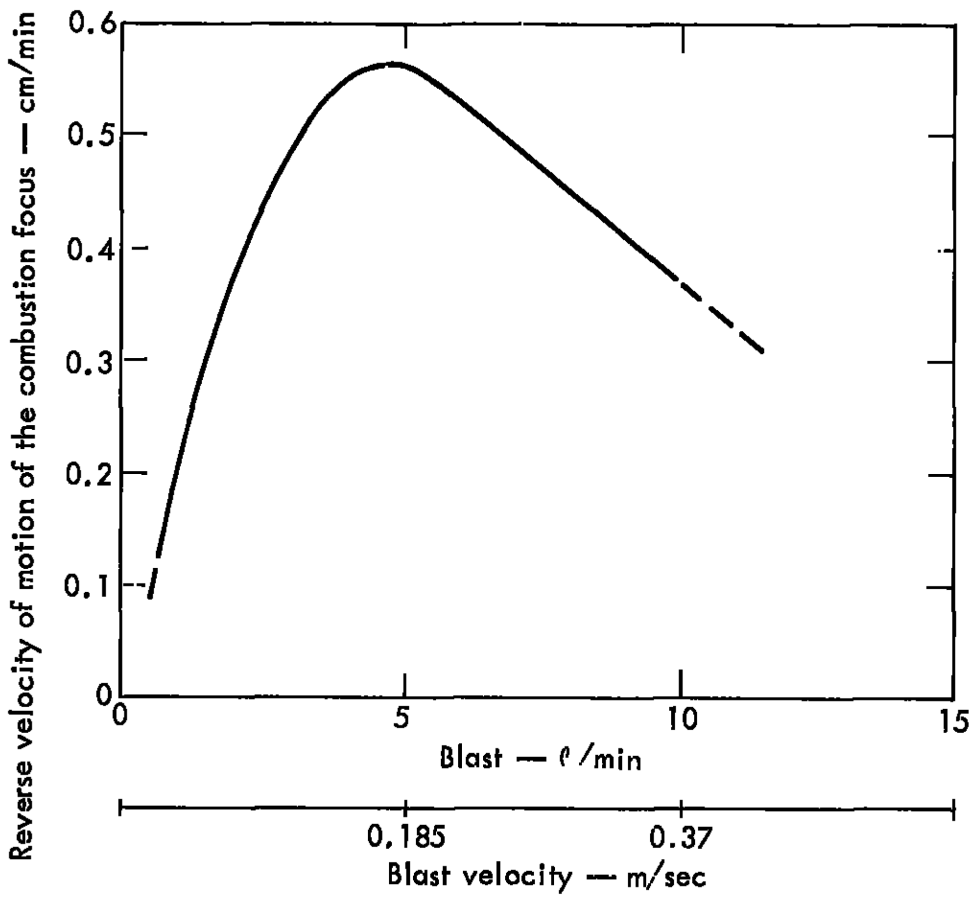

Fig. 31. Dependence of the reverse velocity of the combustion focus on the blast velocity for hard coal. Typical behavior of the velocity of a countercurrent combustion vs blast velocity is shown in this figure. It can be seen that there is an optimum blast velocity which maximizes the flame front velocity. The reason for such a maximum is as follows: the flame front propagates against the gas flow because coal upstream is heated to a flash point; it ignites and consumes all the oxygen. It thus can leave hot, unconsumed coal behind downstream by depriving it of oxygen. The heat conduction upstream is due to thermal conductivity in the coal, as well as radiation. This heat conduction mechanism is competing with the convective heat transfer due to the flowing gas which moves heat downstream. This directional competition of heat transfer, with one being coupled to the blast velocity, results in an optimum blast velocity that gives a maximum countercurrent flame front velocity.[10]

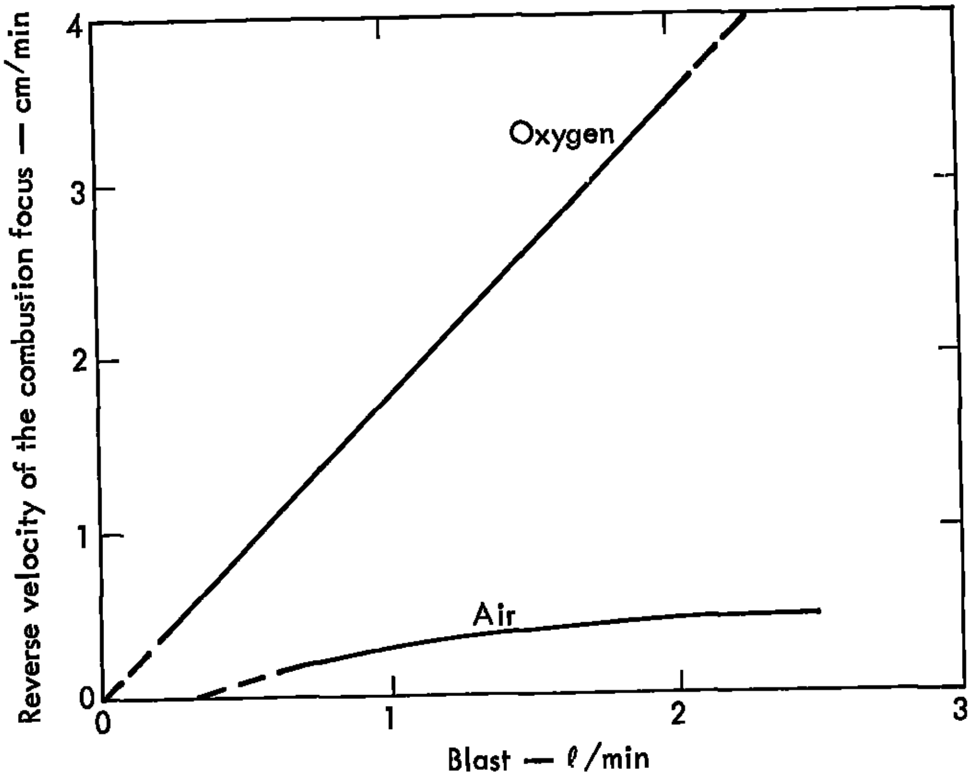

Fig. 32. Change in the velocity of the combustion focus in the reverse direction, for an air blast and a 98% O_2 blast. The gasification channel is in the form of a borehole in a block of Moscow coal. This figure illustrates the difference between air and oxygen for carrying out a countercurrent combustion.[10] It is clearly seen that the flame front velocity is considerably higher if oxygen is used. This can be understood in terms of the oxygen generating a hotter flame front than air at the same flow rate, as well as the coal having a lower ignition temperature in oxygen. However, the Soviets also found that if oxygen is used for linking, the resulting channel had a much lower overall conductivity to gas flow.[23] In fact, the channel conductivity was so small that it was not directly useable for the process. Sometimes a channel burned countercurrently several times with oxygen could be used, but it is not clear that this was an economical approach. They found that air had approximately the optimum oxygen concentration for making, with a single burn, a channel with sufficient permeability and an acceptable flame front velocity.

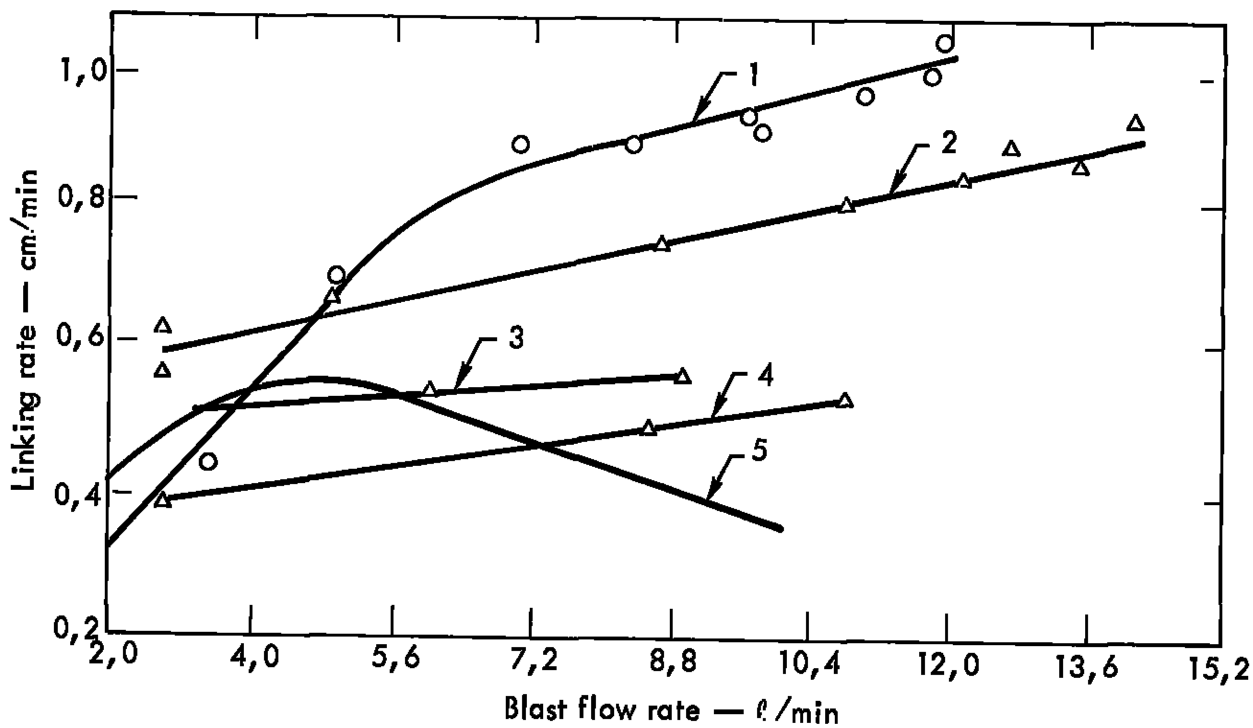

Fig. 33. Rate of linking as a function of the blast-injection rate for various coals. (1) From seam i_3, Kamenskaya Podzemgaz station. (2) From seam V Vnutrennyi, Bunguro-Listvenskii area, Kuzbass. (3) From seam I Vnutrenayi, Bunguro-Listvenskii area. (4) From seam II Vnutrennyi, Bunguro-Listvenckii. (5) From seam l_6, Lisichanskaya station. This figure illustrates the differences in countercurrent combustion velocities for a variety of Soviet coals with air for blast.[10]

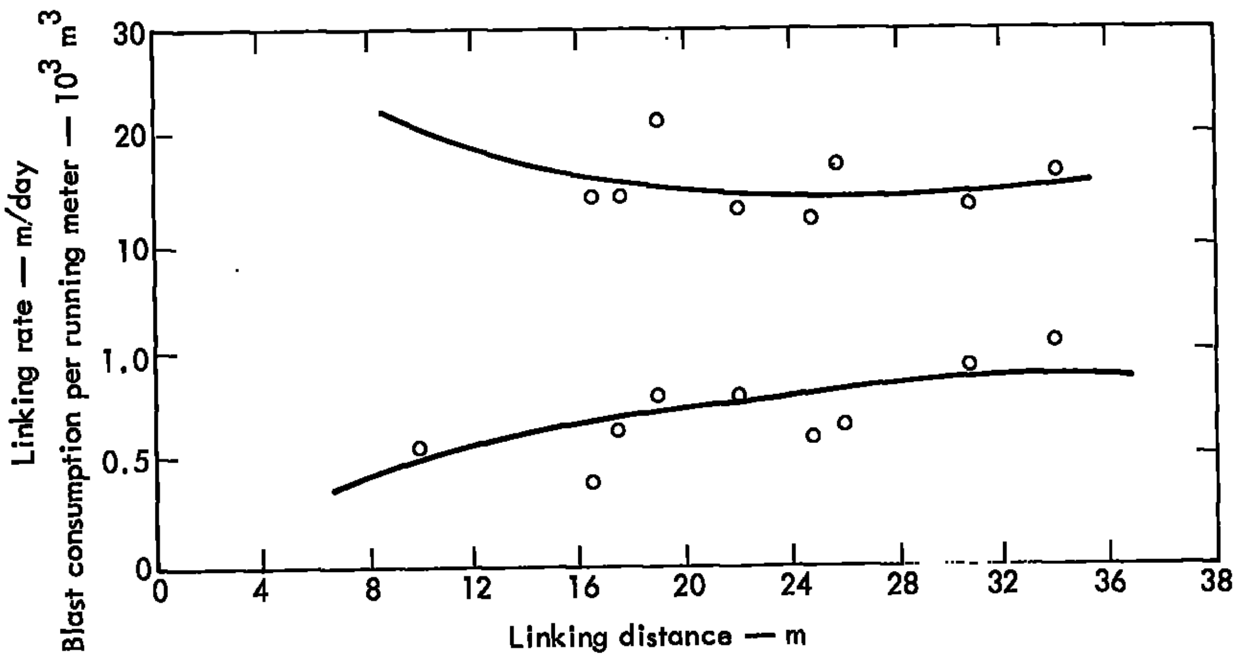

Fig. 34. Change in the velocity of inverse linking and blast consumption per running meter of channel produced, as dependent on the linking distance. This figure is interesting in that it shows that the linking rate and blast consumption per meter of linking are almost independent of the distance between the pipes. This would infer a confined gas-tight zone during linking. This could have been due to the surrounding coal being sealed by being saturated with water, and the formations bounding the coal being very impermeable. It also indicates that subsidence cracks were not contributing to gas leakage, which might be expected since linking takes place in a zone of coal where subsidence has not yet occurred.[10]

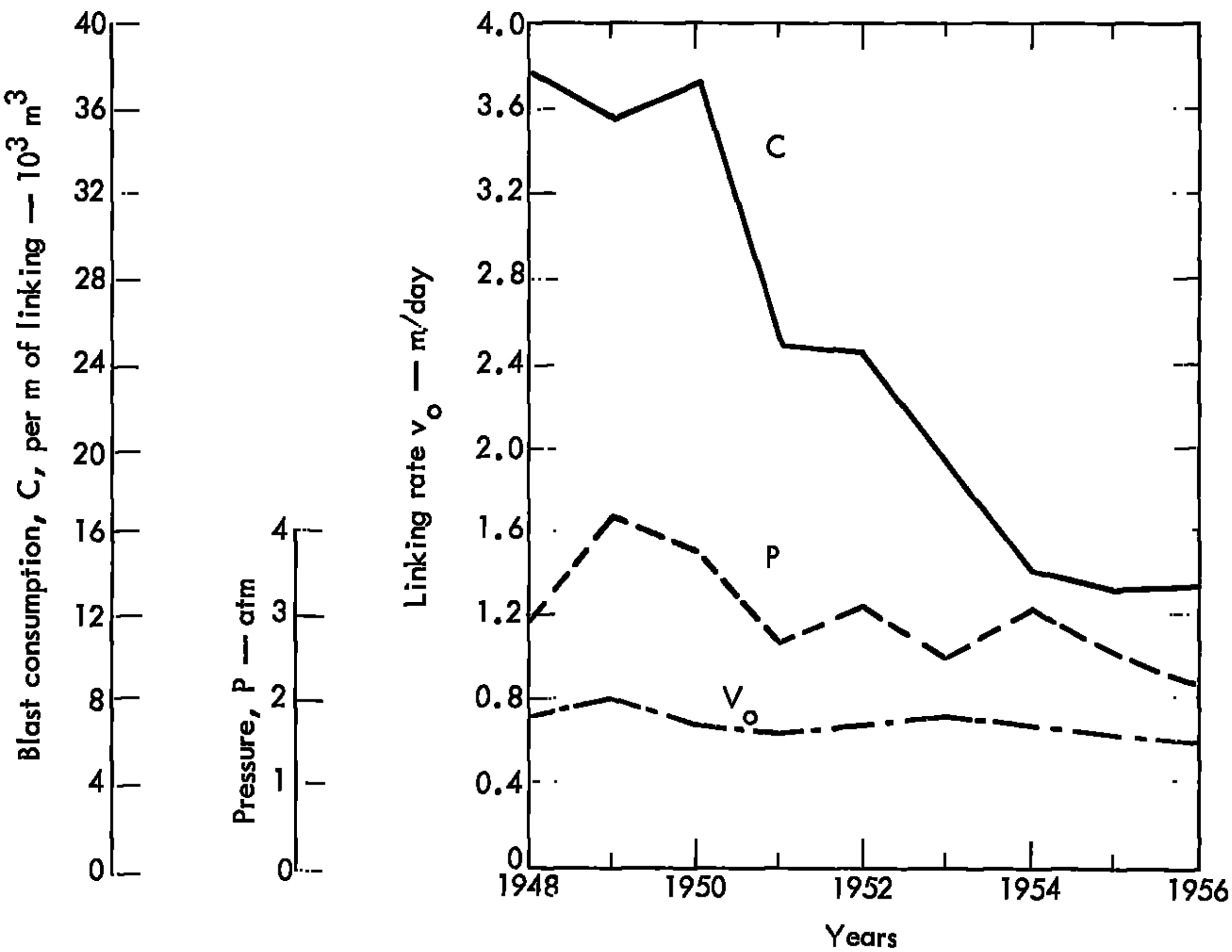

Fig. 35. Change in the characteristic parameters of channeling by burn-through with the use of the permeability of the coal seam, Podmoskovnaya station. The most important feature of this figure is that the Soviets improved their linking technique over these years. This was accomplished by using the directional permeability of the coal; by using a constant blast input rate, instead of a constant blast input pressure; by better shaping of the linking faces of the boreholes; by linking in the direction of the injection holes, instead of in the direction of the gas removal holes; and by linking many parallel hole pairs simultaneously.[10]

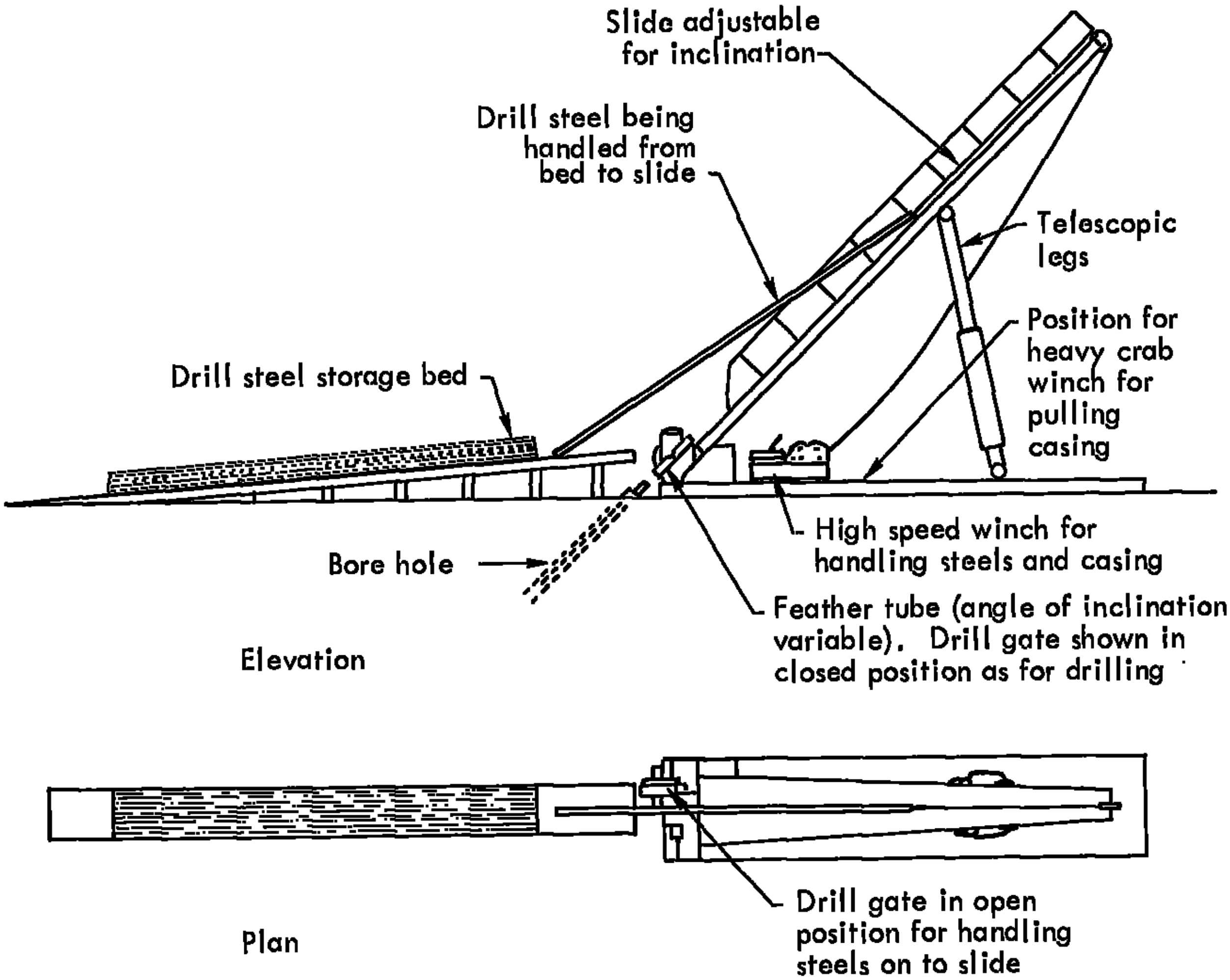

Fig. 36. Sketch of drill rig for inclined, directed boreholes. In addition to countercurrent combustion, the Soviets tested directional drilling, hydrofracking and electrolinking as methods to establish the linking channels. They had favorable results under different conditions with each of these techniques. However, only directional drilling will be covered briefly here. This figure illustrates one of their directional drilling rigs developed for this purpose.[5]

1. The earliest work involved watching drill chips, calculating, and cementing.
2. Later work used a magnitometer and down-hole motor for continuous operation.
3. The best system used shielded Geiger counters to observe gama activity. (Rocks were more gama active than coal.)
4. The Polish invented an 0_2 lance which automatically stayed in coal seam.
   A. It used air at 1.2 to 2.5 atm.
   B. It drilled a hole 22 cm in diameter and progressed 11 m/day.
5. The British used Hg manometers.

Fig. 37. Outline of Soviet directional drilling. This figure presents an outline of some of the Soviet techniques used to sense the location of a drill bit in coal. This is critical to carrying out directional drilling in a coal seam.[5,10,24-27]

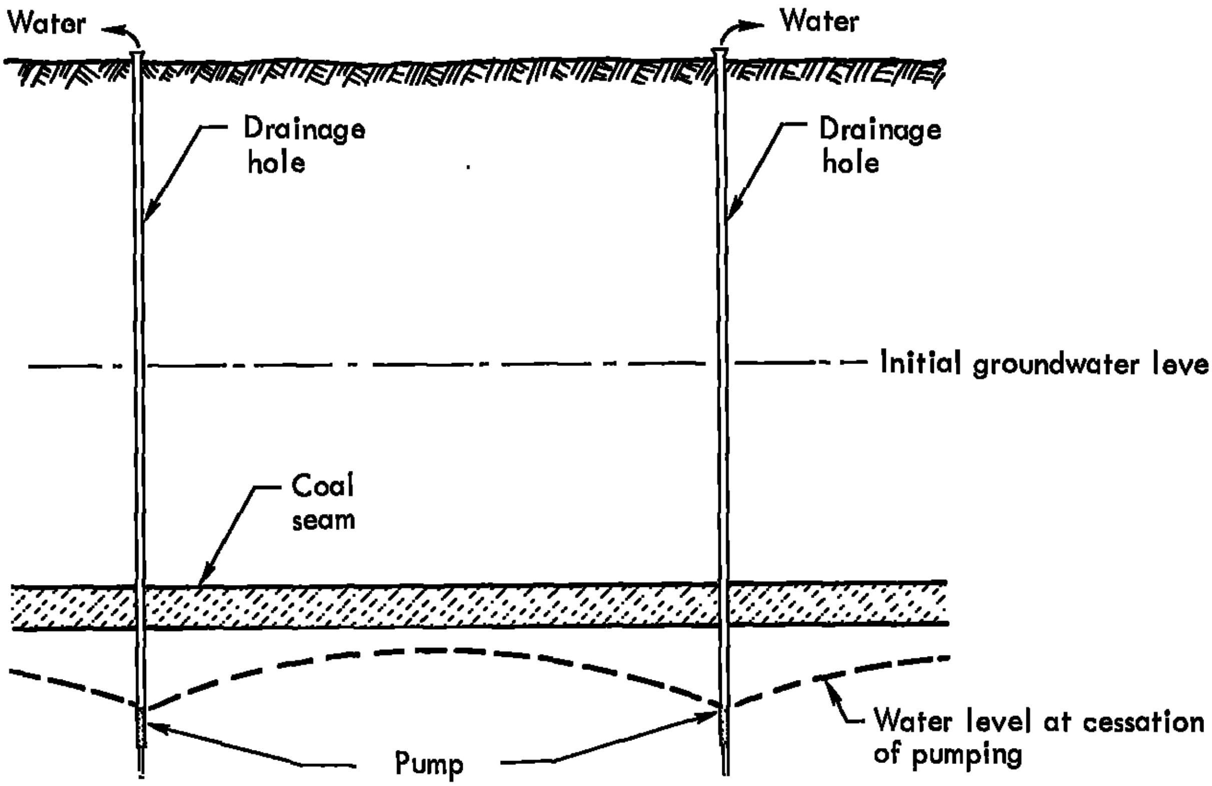

Fig. 38. Scheme for lowering the level of underground water. The Soviets frequently attempted to dewater the coal before or during gasification. When they did so, they attempted to draw the local water table down approximately 1 m below the bottom of the coal seam. This was done primarily to reduce the water intrusion rate into the gasification zone and thus improve the heating value of the product gas. However, this might also be done to help keep a linking channel, created by countercurrent combustion, close to the bottom of the coal seam. Water intrusion during linking would tend to cause such channels to bow up and override some coal between the two access pipes.[10]

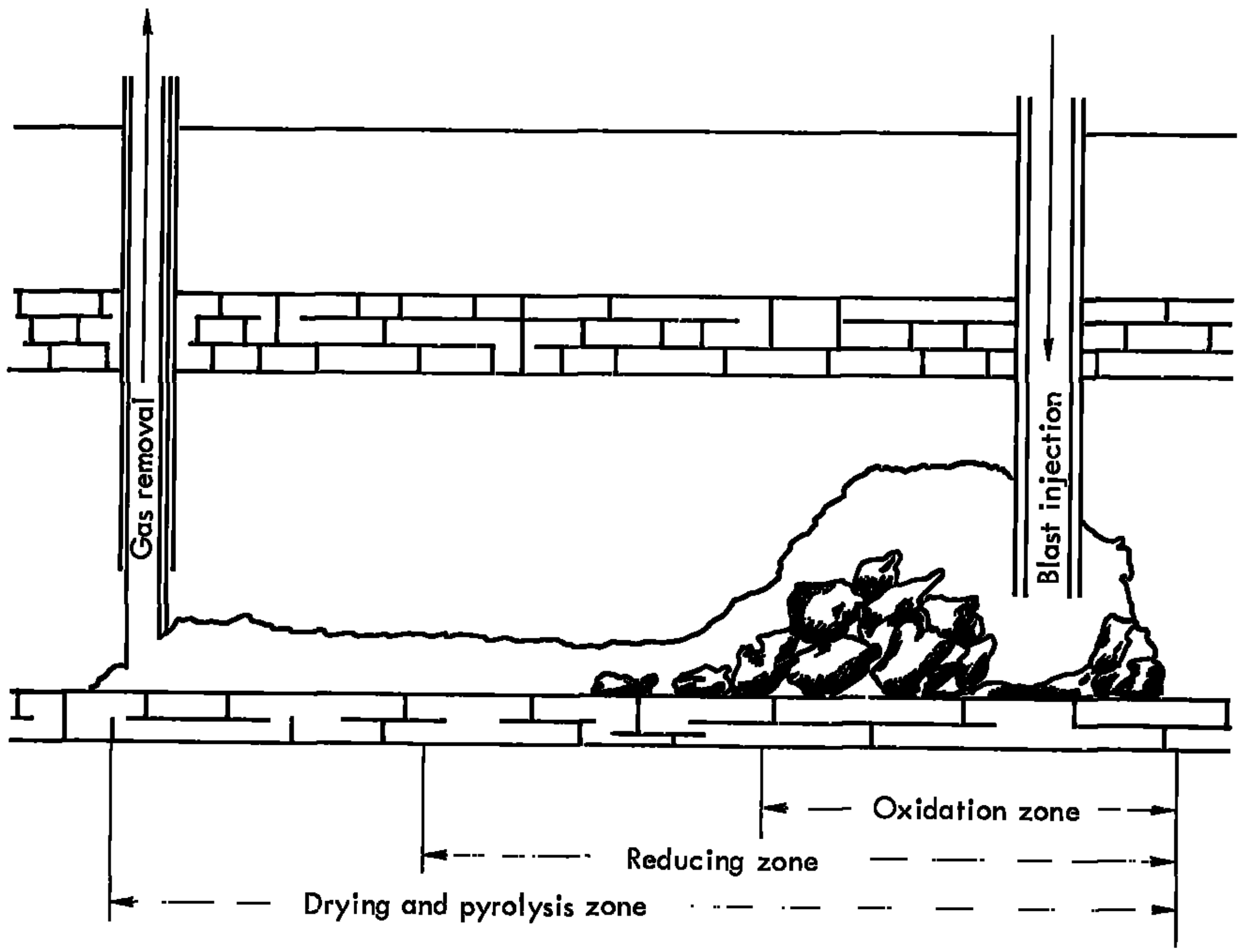

Fig. 39. Conceptual view of a channel during gasification. This figure illustrates how we envision the tip of one of the channels during gasification in a thick coal seam. An essential feature is that as coal is consumed (initially at the bottom of the seam because of the placement of the linking channel) more coal falls into the void created. This creates a high-surface-area packed bed at the tip of each channel, the reduction zone. Such a zone is highly reactive and is responsible for the uniform quality of product gas. These zones are much longer than those in surface reactors due to the nonuniform nature of the packed bed. Further upstream, the channel may widen to many times the coal seam thickness, and this mechanism of coal falling into the void will no longer be as important. Also, a sampling of gas upstream, in the oxidation zone, would show low heating values. However, as long as the tip of each channel is comprised of a hot, highly reactive zone of coal rubble through which all the hot gasses must flow, this zone will insure that the product gas will have a high heating value that is uniform with time.

Station	α	Seam width, h (m)
Luka	9	2–4
Lisichansk	9 (air blast)	1–3
	19 (oxygen-enriched blast)	1–3
Yazhno-Abinsk	7	2
	4	8
British P-5 experiment (Neuman Spinney)	24	0.6–0,8

Fig. 40. The critical channel width. If we imagine a channel that is extended indefinitely with sequentially drilled holes and operated for a long period of time, it is important to know how wide the channel will grow. This will determine the maximum initial hole spacing allowable for 100% resource recovery. With a little thought, we can conclude that the channel will reach a stable width and grow no further. This is because of the fact that as the channel grows in width, the transfer rate of oxygen to the combusting coal faces diminishes while the conductive and radiative heat losses from the faces remain constant or increase. At a particular width (the critical channel width) it is no longer possible to sustain combustion on the faces, and the channel ceases to widen. The value of the critical width will clearly be affected by the permeability distribution in the channel after root subsidence. This figure presents the critical channel widths for the Soviet gasification stations as well as for the British experiment at Neuman Spinney. (Note that the critical channel width, W_{cr}, can be expressed as a constant, α, times the seam width, h. $W_{cr} = \alpha h$.) It can be seen that with air as a blast, the critical channel width is usually 5 to 10 times the seam thickness, and this can be increased by enriching the blast with oxygen. The British went to 25 times the seam thickness with some success, but did leave a considerable amount of coal between the channels.[5,7,28]

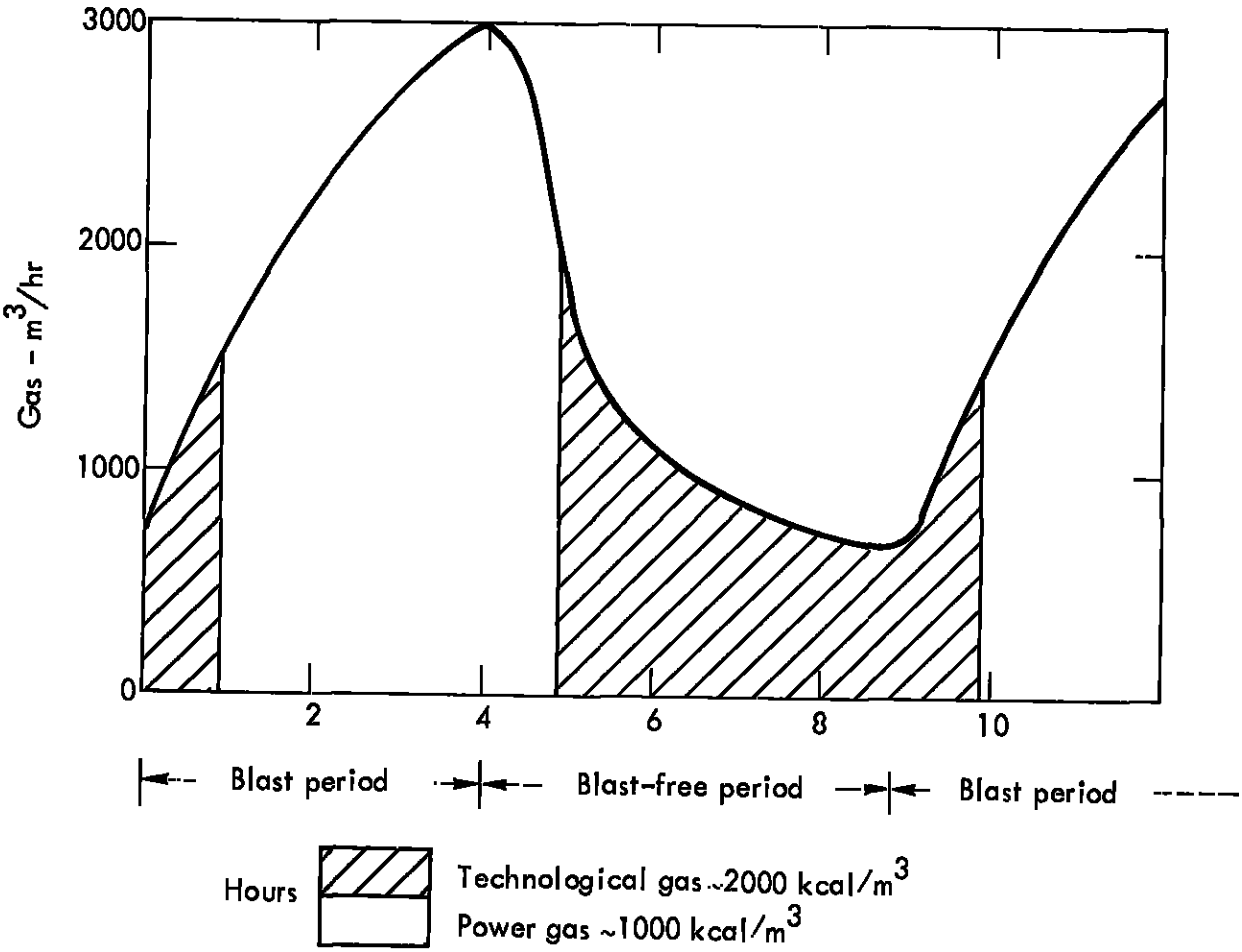

Fig. 41. Change of the amount of gas during operation with and without blast, gas generator No. 1, Gorlovskaya station. The primary point of this figure is to show that in some cases an *in situ* coal gasification station can be turned on and off over a period of a few hours. This might make it useful for an intermediate load electrical generation system. The figure also shows that during gasification with air, the product gas is the typical low Btu gas obtained with an air blast. However, if the air is turned off, we obtain, for a while, pyrolysis gas (methane, hydrogen, etc, and no nitrogen), a gas composition that has a much higher heating value.[10]

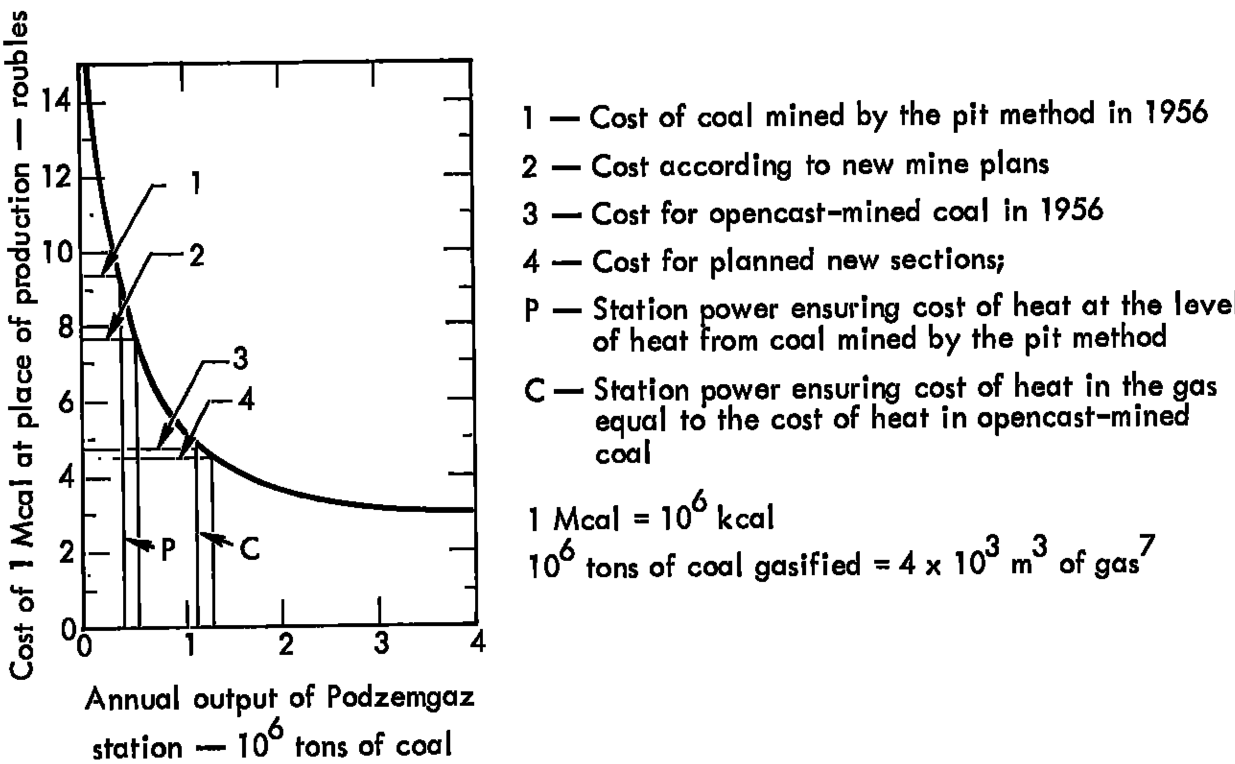

Fig. 42. Calculated change in the cost of 1 Mcal in the gas at place of production for Kuzbass conditions as a function of the power of the Podzemgaz station. This figure presents typical economic calculations[10] made on underground coal gasification in the USSR. All such published calculations we found showed that underground gasification above a certain production rate was more than competitive with other means of extracting coal. However, all such calculations[11,29-33] are suspect in terms of being able to transfer them into our economic system, especially taking into account improved technology in all fields of coal extraction.

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